Search for Exotic Hadrons in $\eta^{(\prime)}\pi$ at GlueX

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for the GlueX Collaboration

Jefferson Lab

20th International Conference on Hadron Spectroscopy and Structure
(HADRON 2023, Genova, Italy)

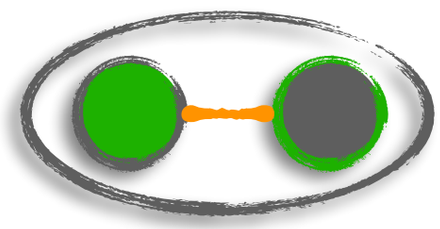
06 / 06 / 2023

Beyond the Constituent Quark Model

- Minimal allowed bound states of QCD: Mesons ($q\overline{q}$) and baryons (qqq)
- For mesons: $P = (-1)^{L+1}$ and $C = (-1)^{L+S}$

  Allowed: $J^{PC} = 0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, ...$
  Forbidden: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, ...$

- Observation of state with J^{PC} forbidden for $q\overline{q}$: clear evidence for exotics
- Understanding QCD: What is the role of gluons (generation of mass, spin, …)?
- Configurations with additional gluonic degrees of freedom allowed:



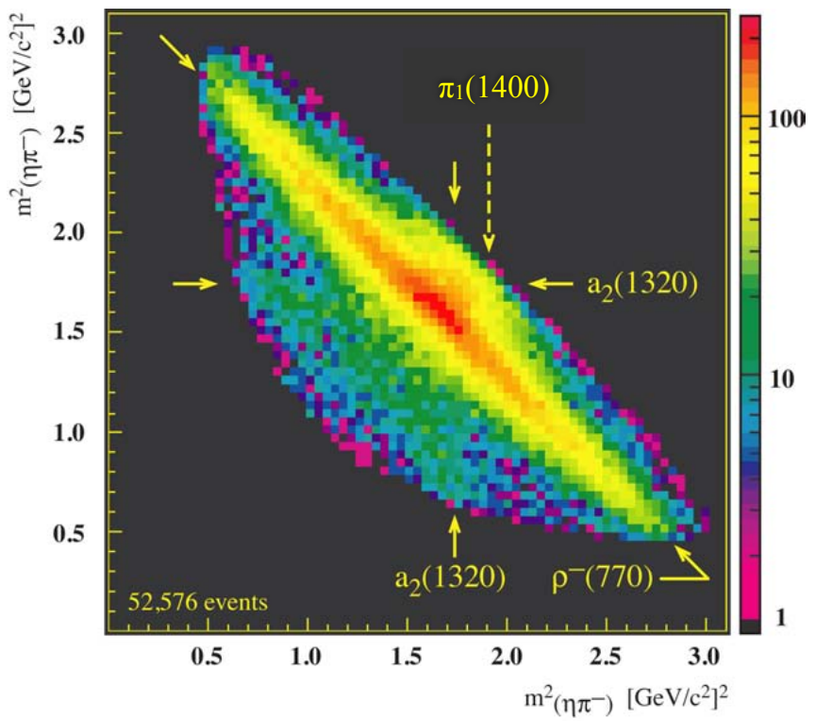
- Hybrids (mesons with excited gluonic degrees of freedom)

- Glueballs
  (no valence quark content)

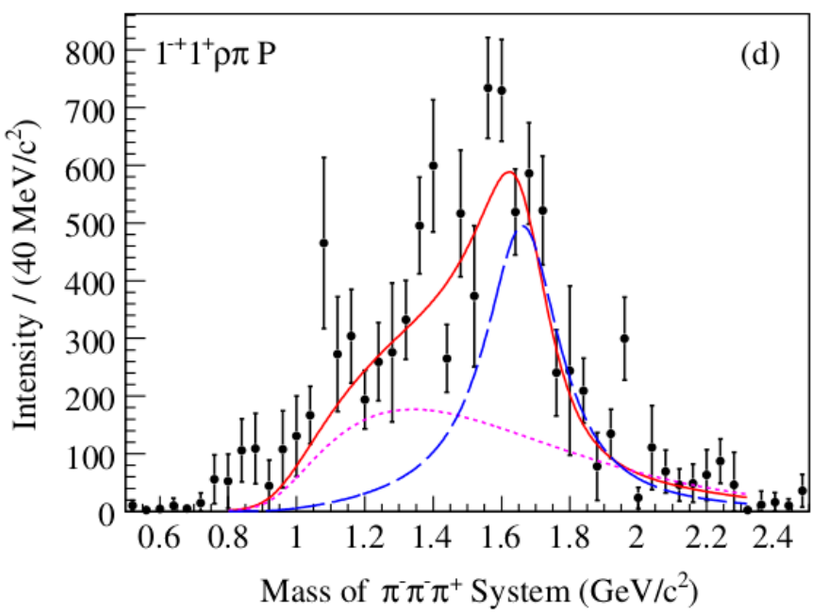
Hybrid search: Primary motivation for the construction of Hall-D / GlueX

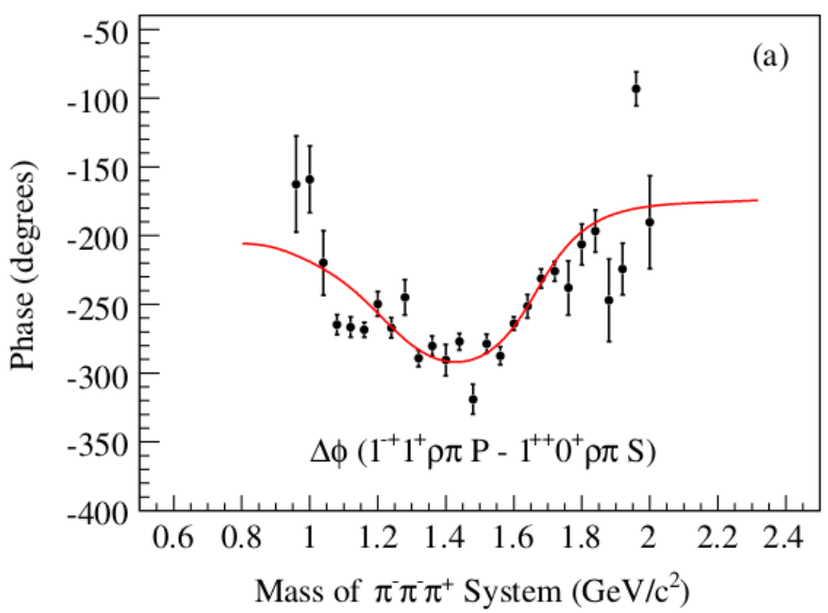
Hybrid Mesons

PLB 423, 175-184 (1998), Crystal Barrel

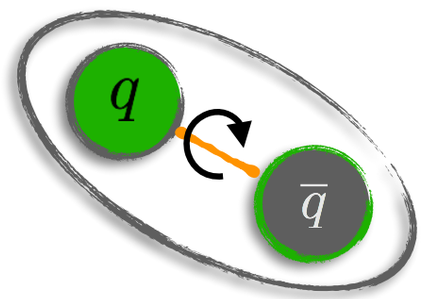


PRL 104, 241803 (2010), COMPASS





- Hints for spin-exotic states already in 1980s
- Observed at various experiments
- From PWA: $J^{PC} = 1^{-+}$
  - $\pi_1(1400)$ in $\eta\pi$
  - $\pi_1(1600)$ in $\eta'\pi, \rho\pi$
- Clear contribution of exotic wave
- Two genuine resonances?



The $\eta^{(\prime)}\pi$ System

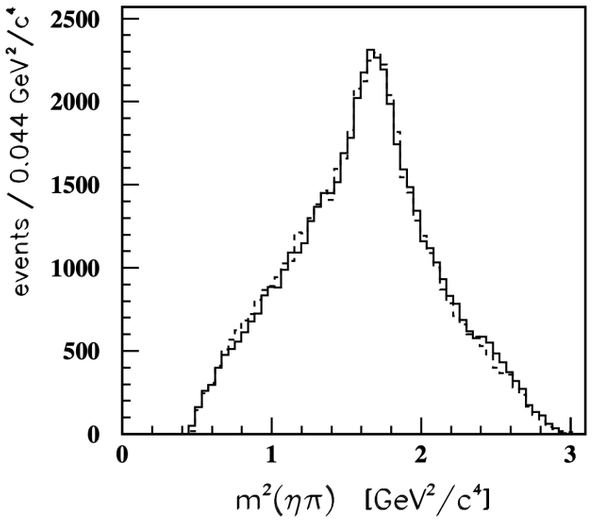
- Strongest evidence for π_1 contribution in $\eta\pi, \eta'\pi$ and $\rho\pi$ channels in πN and $\bar{p}p$ reactions
- Possible J^{PC} states for $\eta^{(\prime)}\pi$ system with orbital angular momentum L:

L	0	1	2	3	...
	S	P	D	F	
J^{PC}	0^{++}	1^{-+}	2^{++}	3^{-+}	...

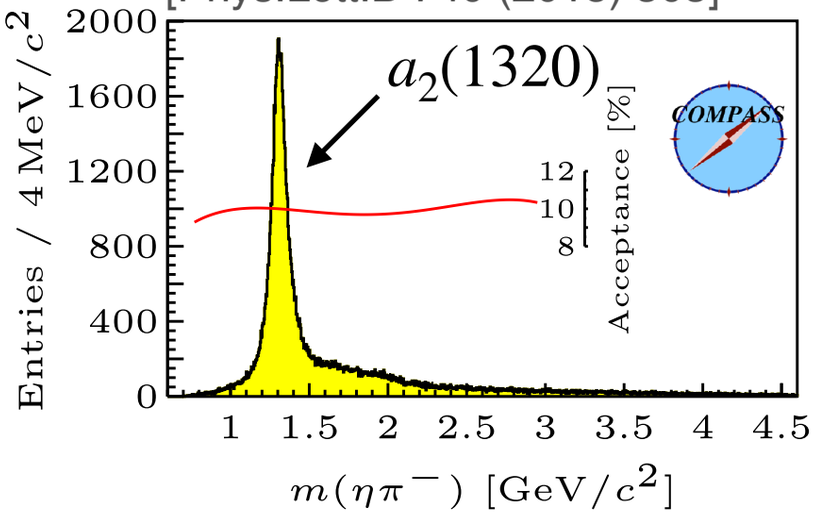
➡ $\eta^{(\prime)}\pi$ in an odd wave ($P, F, \ldots$) has exotic quantum numbers

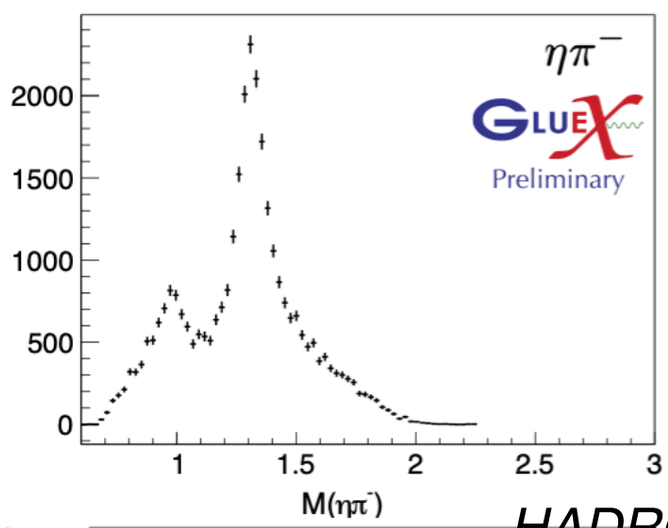
- **High priority for GlueX**
  → Investigating in parallel:
  $\gamma p \to \eta\pi^0 p,\ \eta\pi^-\Delta^{++},\ \eta'\pi^0 p,\ \eta'\pi^-\Delta^{++}$

[Phys.Lett.B 423 175-184 (1998)]



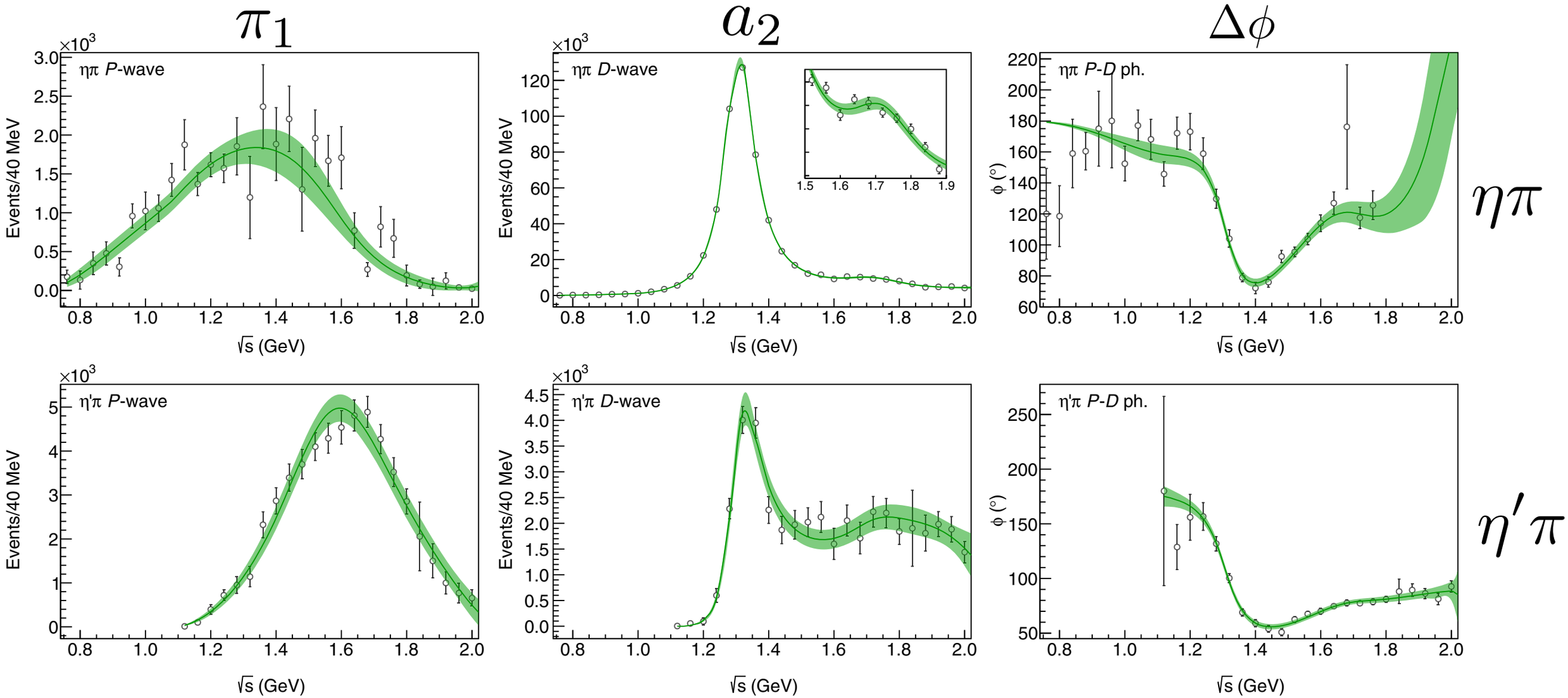
[Phys.Lett.B 740 (2015) 303]



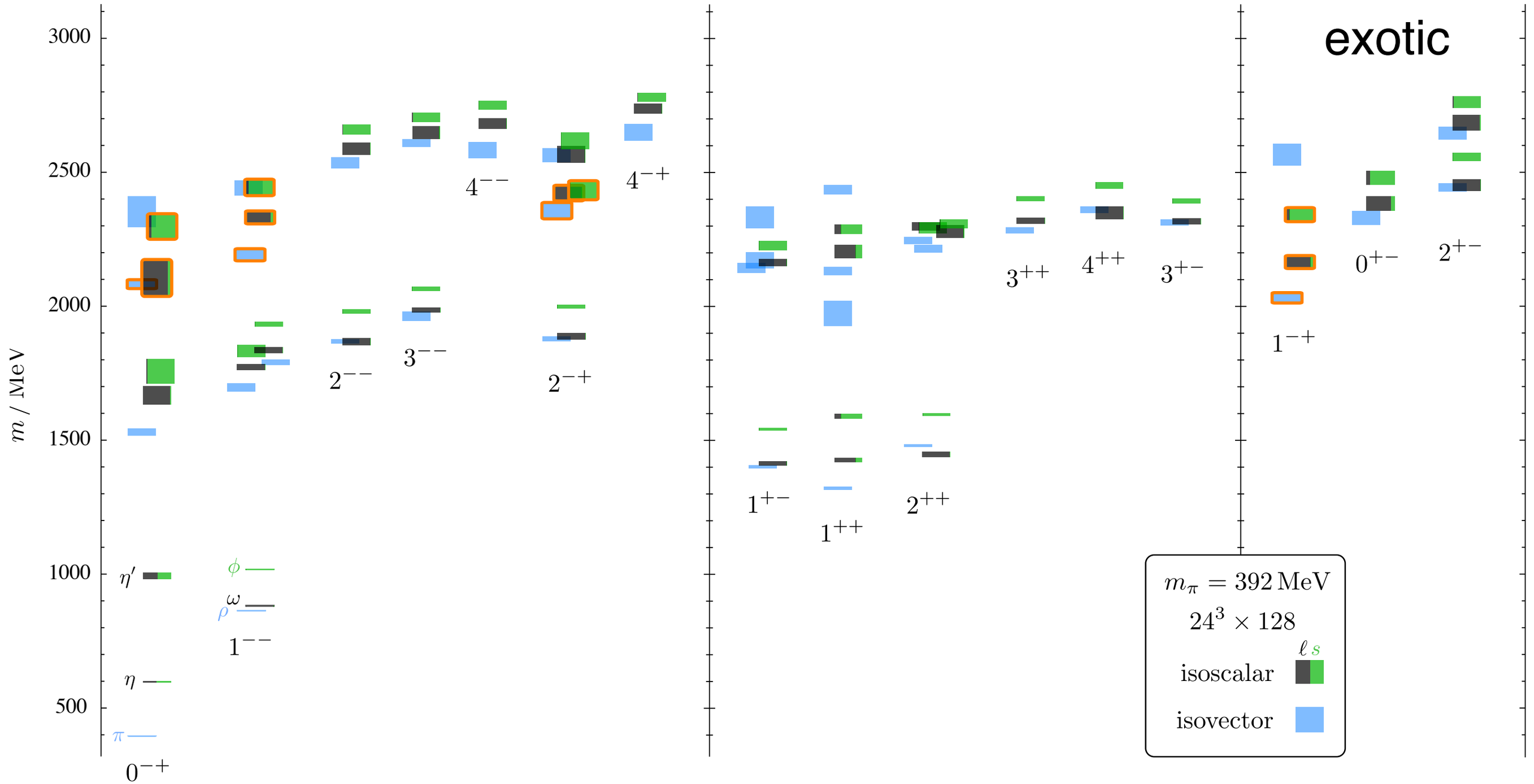


Two Hybrid Mesons?

- Analysis of COMPASS data from JPAC, recently extended with $\bar{p}p$ data:
  [A.Rodas et.al. PRL 122, 042002 (2019), B.Kopf et.al. Eur.Phys.J.C 81, 1056 (2021)]
- Sophisticated description of 1^{-+} wave with 1-pole, 2-channels
- Observed structures described by a single resonance



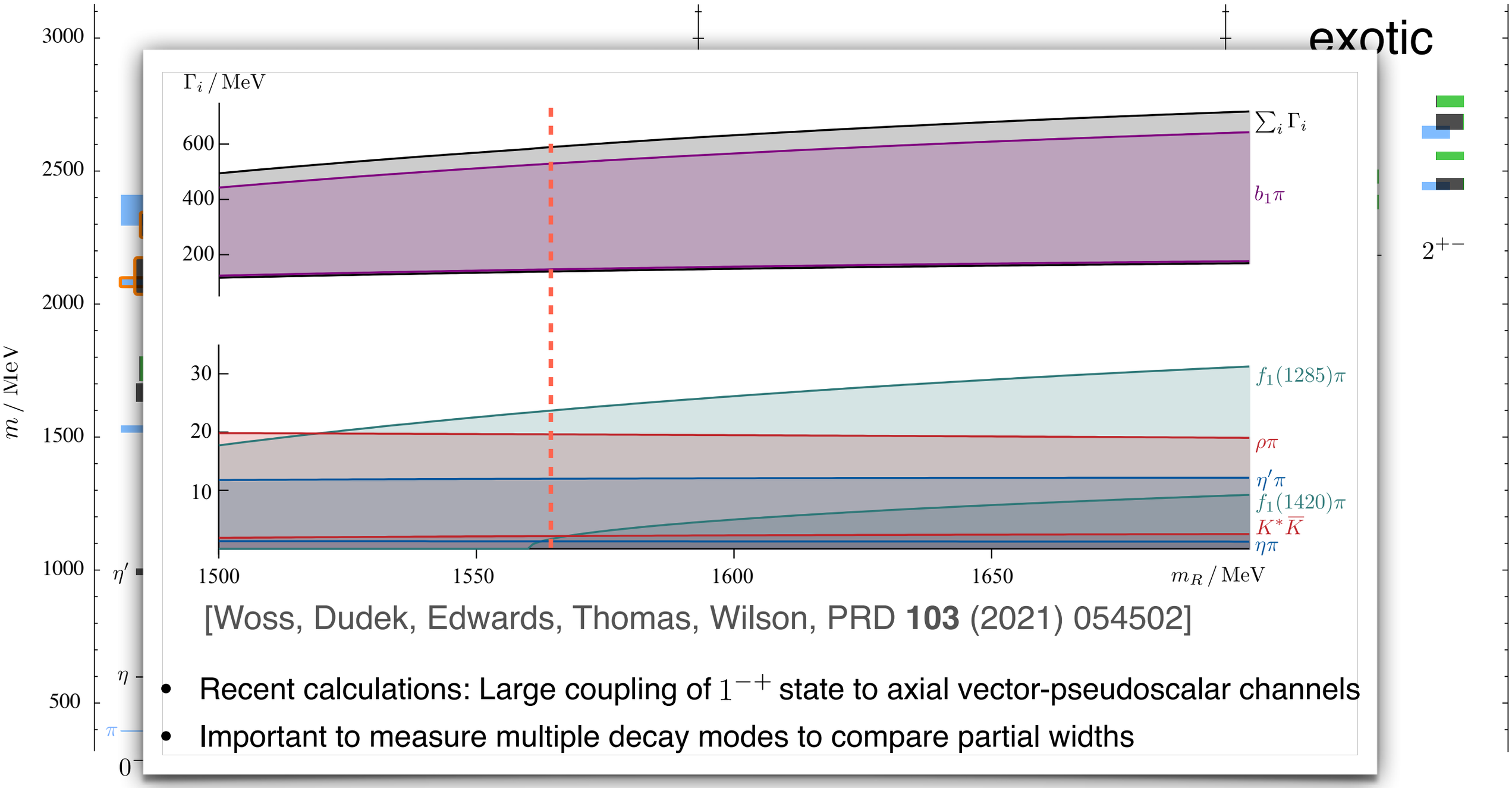
Light Quark Mesons from Lattice QCD



[Dudek, Edwards, Guo, Thomas, PRD **88** 094505(2013)]

- Lightest spin-exotic state: $J^{PC} = 1^{-+}$

Light Quark Mesons from Lattice QCD



[Woss, Dudek, Edwards, Thomas, Wilson, PRD **103** (2021) 054502]

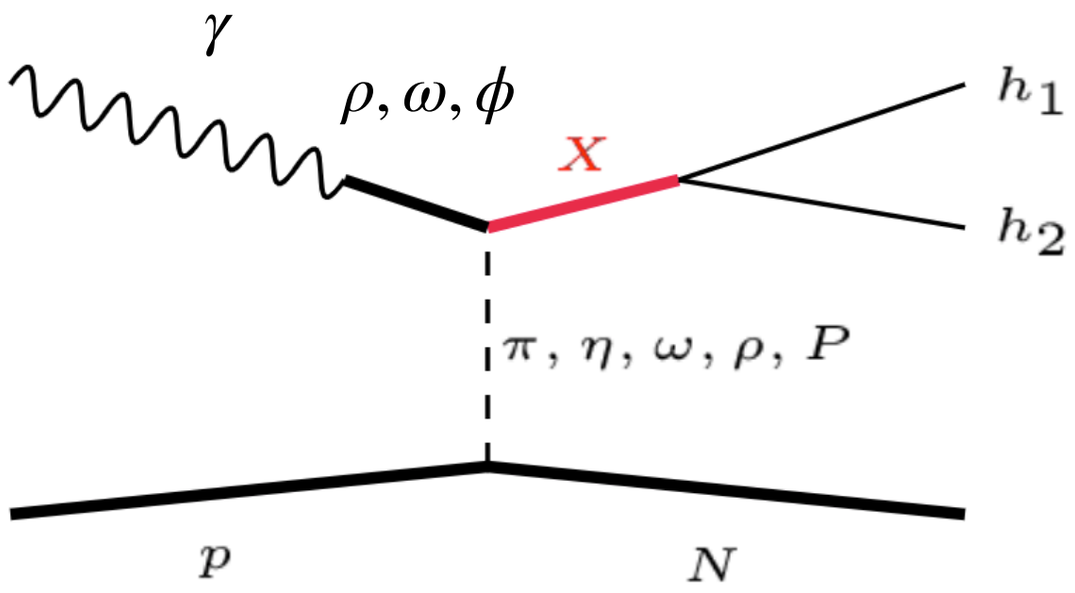
- Recent calculations: Large coupling of 1^{-+} state to axial vector-pseudoscalar channels
- Important to measure multiple decay modes to compare partial widths

[Dudek, Edwards, Guo, Thomas, PRD **88** 094505(2013)]

- Lightest spin-exotic state: $J^{PC} = 1^{-+}$

The Route to Exotics with GlueX

- **Photoproduction - a versatile process:**
  - Incoming photon may oscillate to vector meson
  - Production of mesonic resonances as well as target excitations
  - Complementary to πN reaction used by COMPASS, E852, VES
  - Allows coupling to all lightest hybrid nonet states

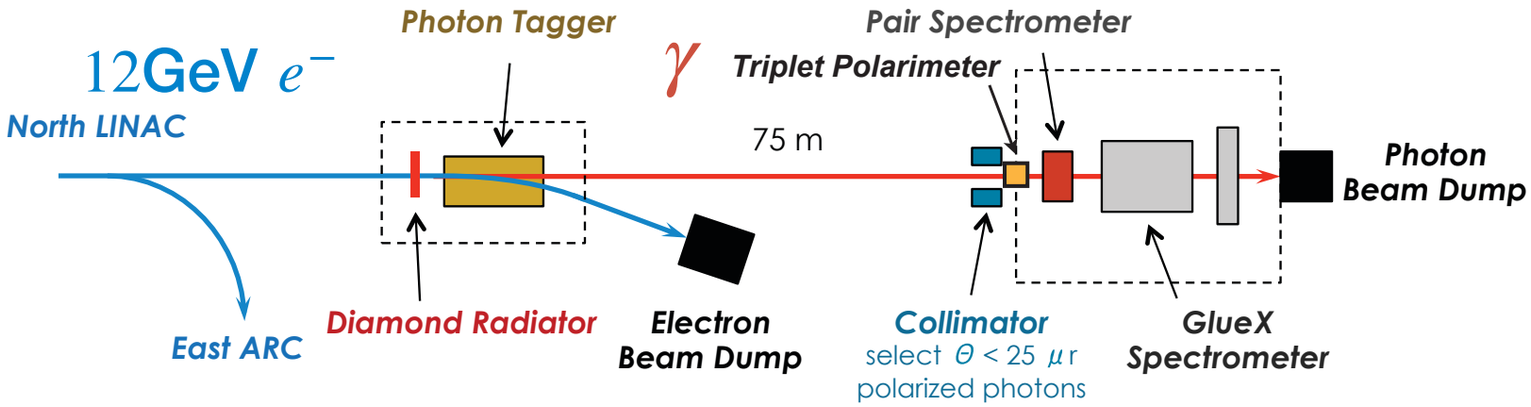


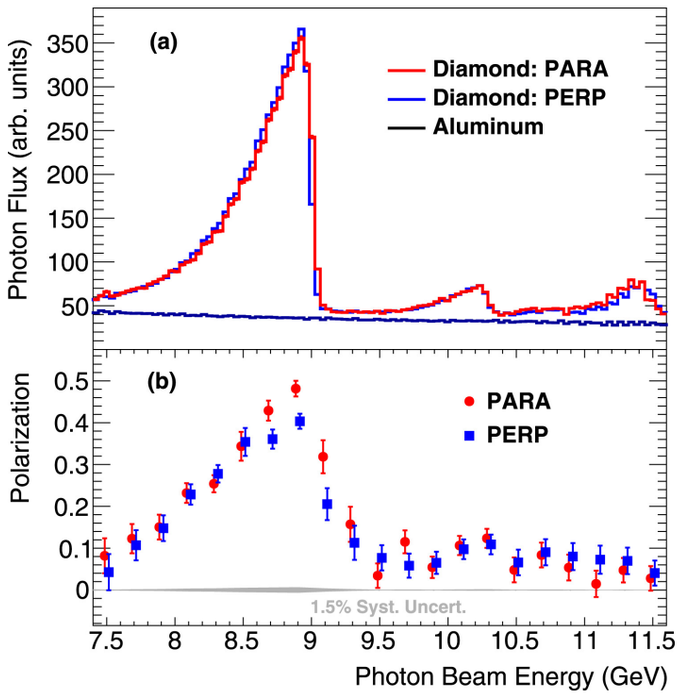
- Understand (polarized) production of “simple” hadrons - increase complexity stepwise
- Achieve good understanding of acceptance and backgrounds
  - **Single pseudoscalar production asymmetries**
    [GlueX, PRC 95 (2017) 042201; PRC, 100 (2019) 052201; PRC 103 (2021) 022201]
  - **Spin density matrix elements ($\rho, \omega, \Lambda(1520)$ -** PRC 105, 035201 (2022)**)**

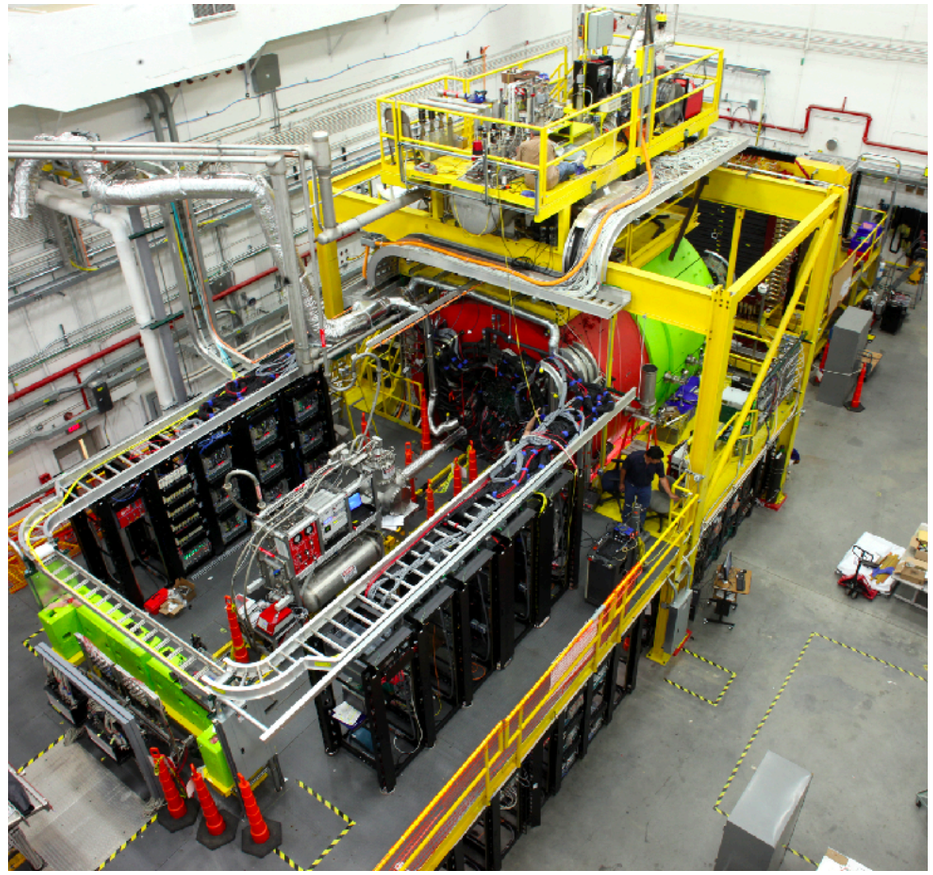
See talk by Alex Austregesilo: Fri, 9am!

- Investigation of $\eta^{(\prime)}\pi$ channels
  - **Study production mechanism, cross section of known mesons first**
  - Charged and neutral modes, different sub-decays → acceptance, background handling
- Extend hybrid search to vector-pseudoscalar channels ($\omega\pi, \omega\eta, \phi\pi, \phi\eta, K^*K$)
  (see talk by Amy Schertz: Fri, 10:35am!)

Hall-D at Jefferson Lab



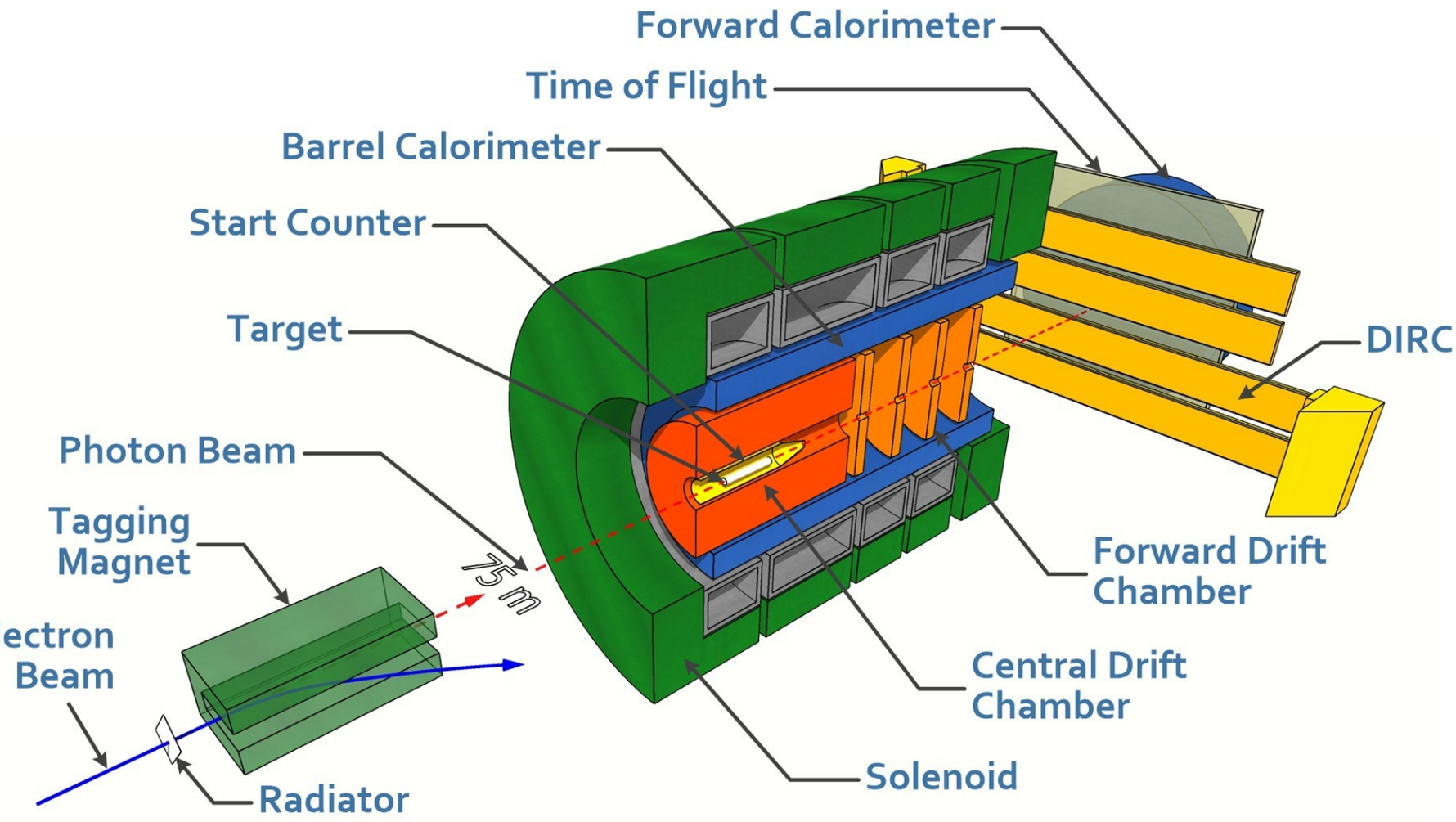




- JeffersonLab: Four main experimental halls
- CEBAF accelerator provides 12 GeV electron beam
- Hall-D: Linearly polarized photon beam produced via bremsstrahlung from thin radiator

The GlueX Experiment

[(GlueX) NIMA **987** (2021) 164807]



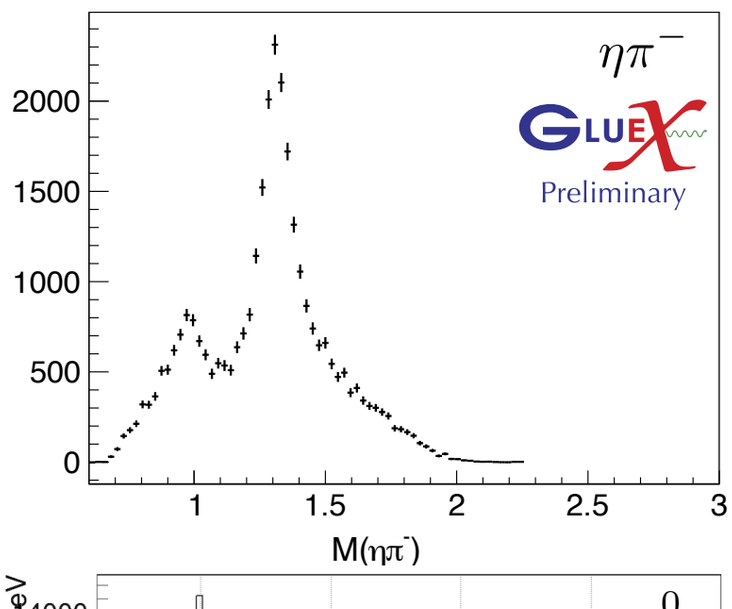
- Linearly polarized, tagged photon beam (P≈40%) impinging on Liquid Hydrogen Target
- Four polarization orientations, coherent peak: ~8.2-8.8 GeV
- Large acceptance for charged and neutral final state particles
- GlueX Phase I completed (2017-18, $\int L = 125\,\mathrm{pb}^{-1}$), Phase II ongoing (expect 3-4 times Phase I data)

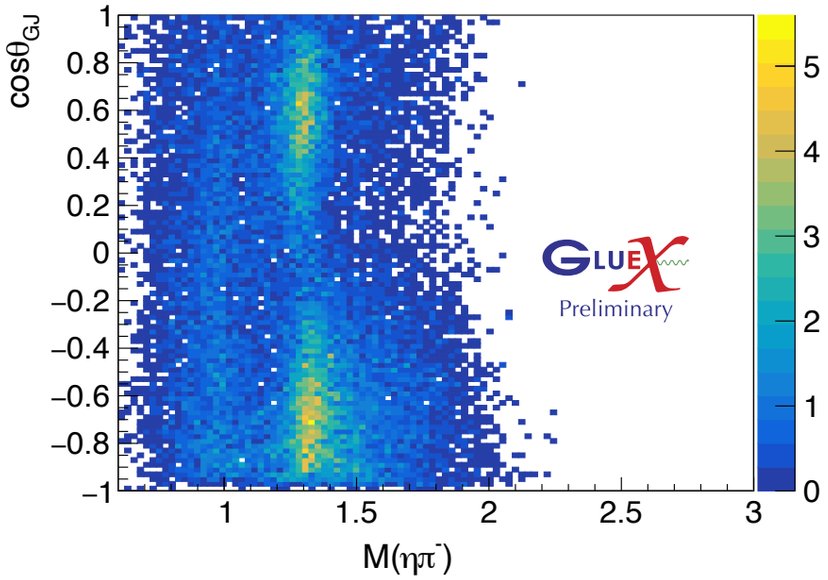
$\gamma p \to \pi\eta N$ at GlueX

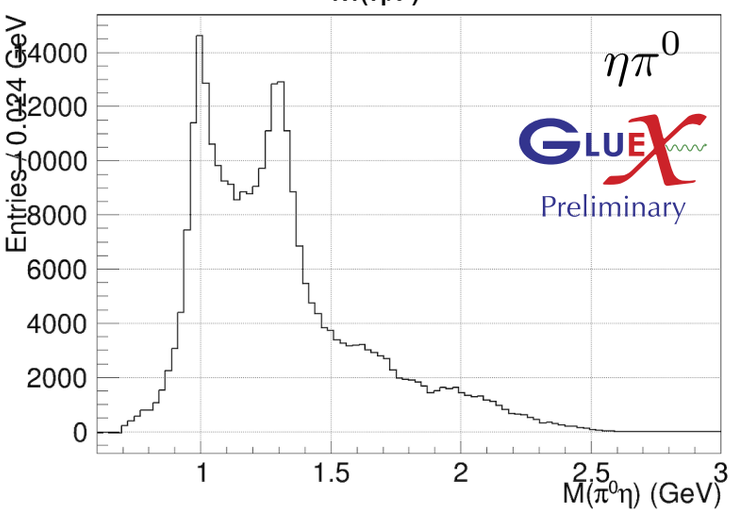
- Evidence for spin-exotic contribution from other experiments
  → Key channel for GlueX

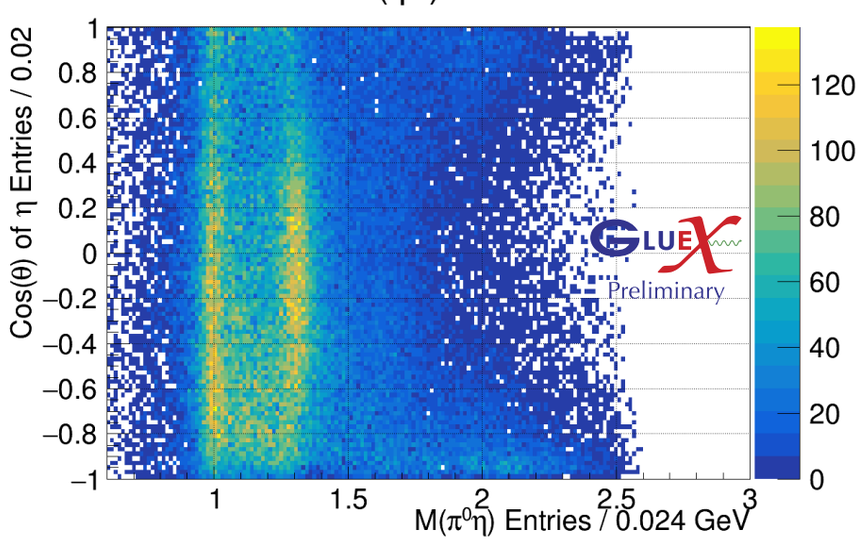
- Clear signals at $a_0(980)$ and $a_2(1320)$ masses

$0.1 < -t < 0.3$ GeV^2









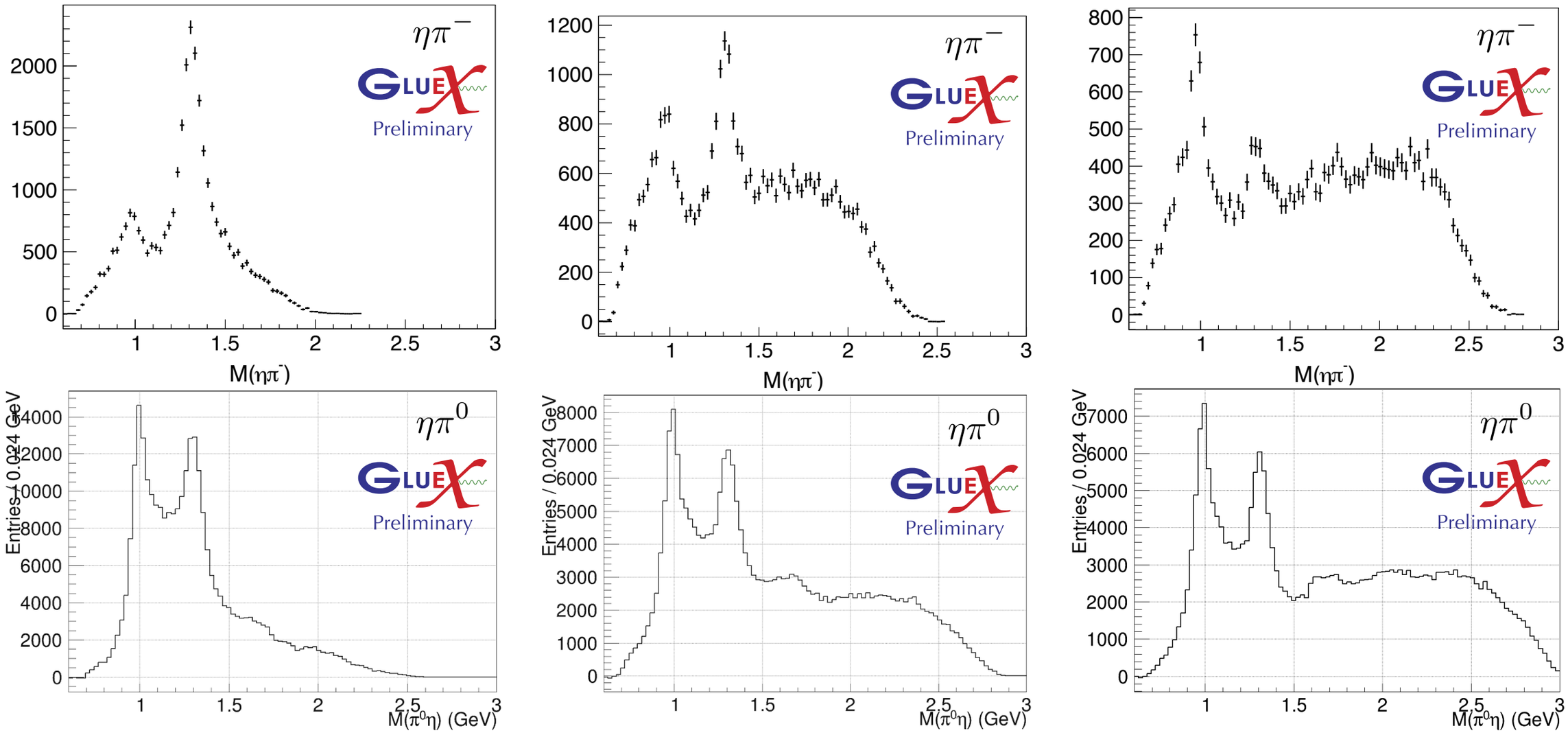
- Angular distribution of $a_2(1320)$ signal clearly different between charged and neutral channels

- Different spin-projection states populated in charged vs. Neutral channel

$\gamma p \to \pi\eta N$ at GlueX

- Evidence for spin-exotic contribution from other experiments
  → Key channel for GlueX
- Clear signals at $a_0(980)$ and $a_2(1320)$ masses

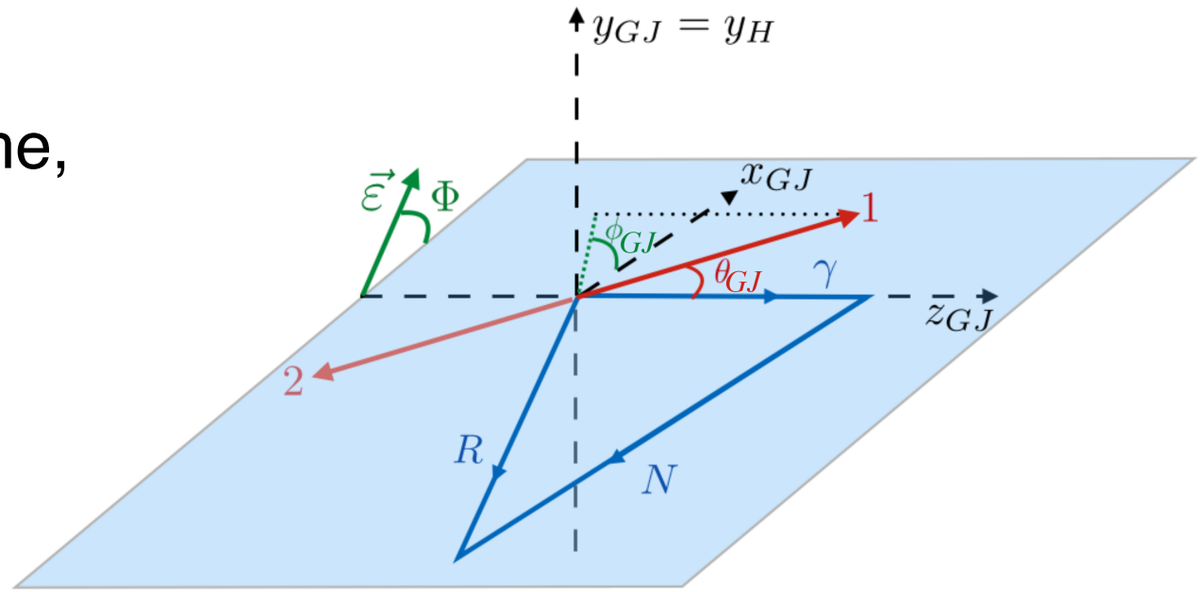
$0.1 < -t < 0.3$ GeV^2 | $0.3 < -t < 0.6$ GeV^2 | $0.6 < -t < 1.0$ GeV^2



Definition of Amplitudes

- Described by three angles:
  $\cos\theta_\eta$ and ϕ_η in the resonance rest frame,
  angle Φ between polarization vector
  and production plane

- Amplitudes incorporate beam polarization, are eigenstates of reflectivity $\epsilon = \pm 1$



[V.Mathieu et.al. (JPAC), PRD100(2019) 5, 054017]

- High-energy t-channel picture: ‘reflectivity’ fixes the product of naturalities of the exchange particle and the produced resonance

  Naturality: $\eta = P(-1)^J$

  natural parity $\eta = +1$ for: $J^P = 0^+, 1^-, 2^+, \ldots$

  unnatural parity $\eta = -1$ for: $J^P = 0^-, 1^+, 2^-, \ldots$

- In case of $\eta\pi$:
  positive (negative) reflectivity = natural (unnatural) parity exchange

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  $\cos\theta_\eta$ and ϕ_η in the resonance rest frame,
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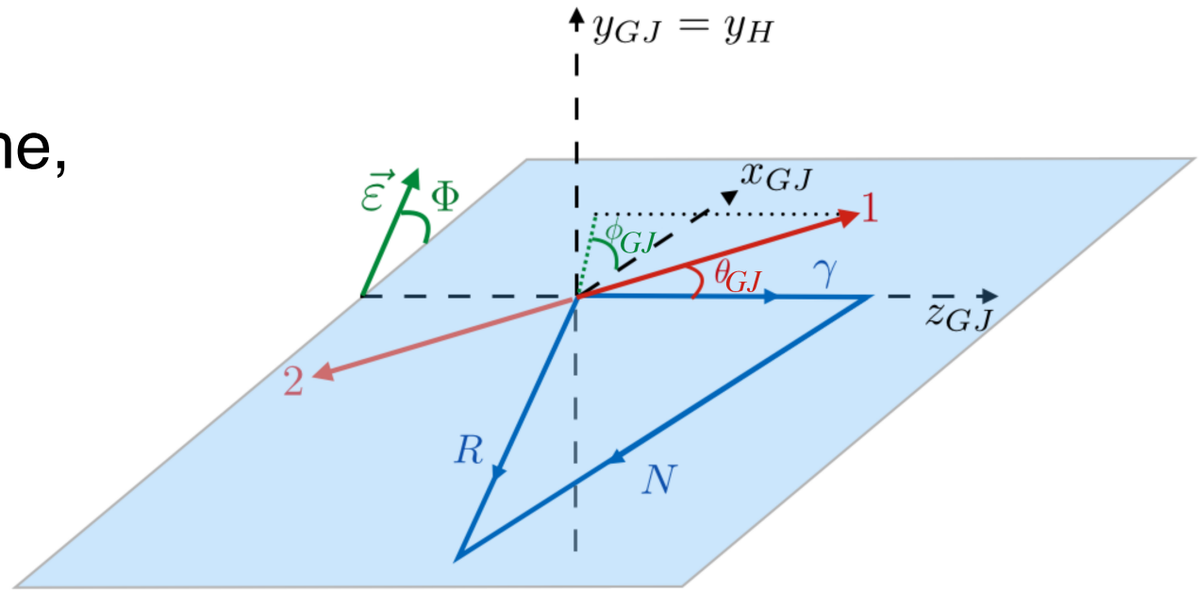


[V.Mathieu et.al. (JPAC), PRD100(2019) 5, 054017]

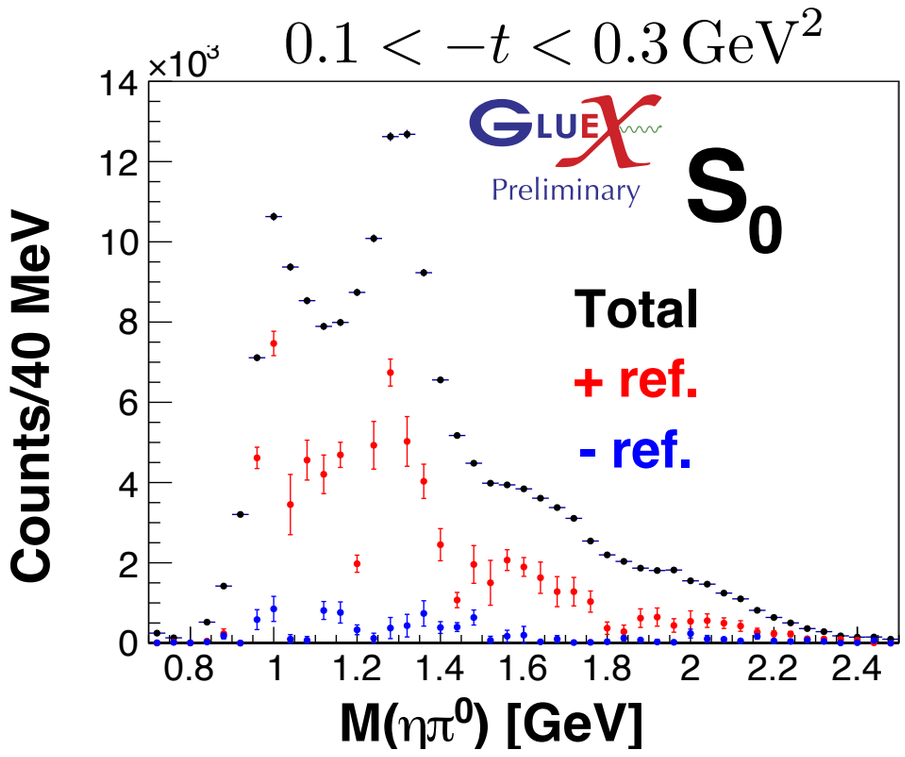
- Basis: Z_l^m amplitudes defined as $Z_l^m(\Omega,\Phi) = Y_l^m(\Omega)e^{-i\Phi}$

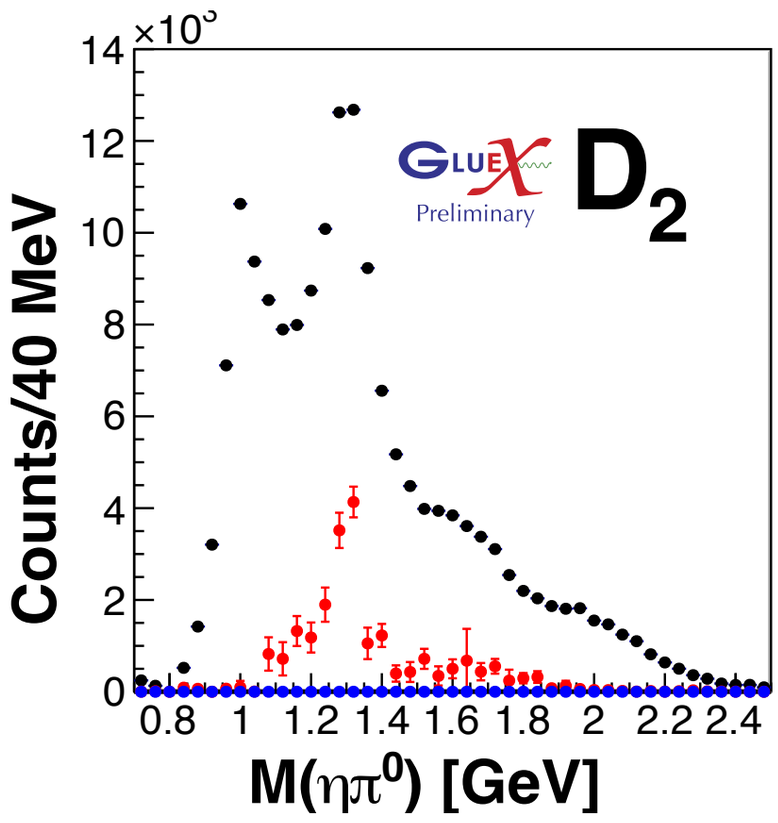
$$I(\Omega,\Phi) = 2\kappa \sum_k \Bigg\{ (1-P_\gamma)\left|\sum_{\ell,m}[\ell]^{(-)}_{m;k}\mathrm{Re}[Z^m_\ell(\Omega,\Phi)]\right|^2 + (1-P_\gamma)\left|\sum_{\ell,m}[\ell]^{(+)}_{m;k}\mathrm{Im}[Z^m_\ell(\Omega,\Phi)]\right|^2 +$$
$$(1+P_\gamma)\left|\sum_{\ell,m}[\ell]^{(+)}_{m;k}\mathrm{Re}[Z^m_\ell(\Omega,\Phi)]\right|^2 + (1+P_\gamma)\left|\sum_{\ell,m}[\ell]^{(-)}_{m;k}\mathrm{Im}[Z^m_\ell(\Omega,\Phi)]\right|^2 \Bigg\}$$

- Complexity: Reflectivity $\epsilon = \pm 1$ and spin projections $m = -l, \ldots, +l$ allowed

- Frequent exchange with JPAC

Mass-Indep. PWA of $\gamma p \to \eta\pi^0 p$





- Combined fit of all polarization orientations
- Large S-wave, positive reflectivity contribution
  - Non-resonant?
  - Contribution from other resonance(s)?
- Clear signal in $m = +2$ D-wave
- Waveset based on Tensor Meson Dominance model:

$$L_m^{\epsilon} = S_0^{\pm}, D_0^{\pm}, D_1^{\pm}, D_2^{+}, D_{-1}^{-}$$

[V.Mathieu et.al. (JPAC) PRD 102, 014003 (2020)]

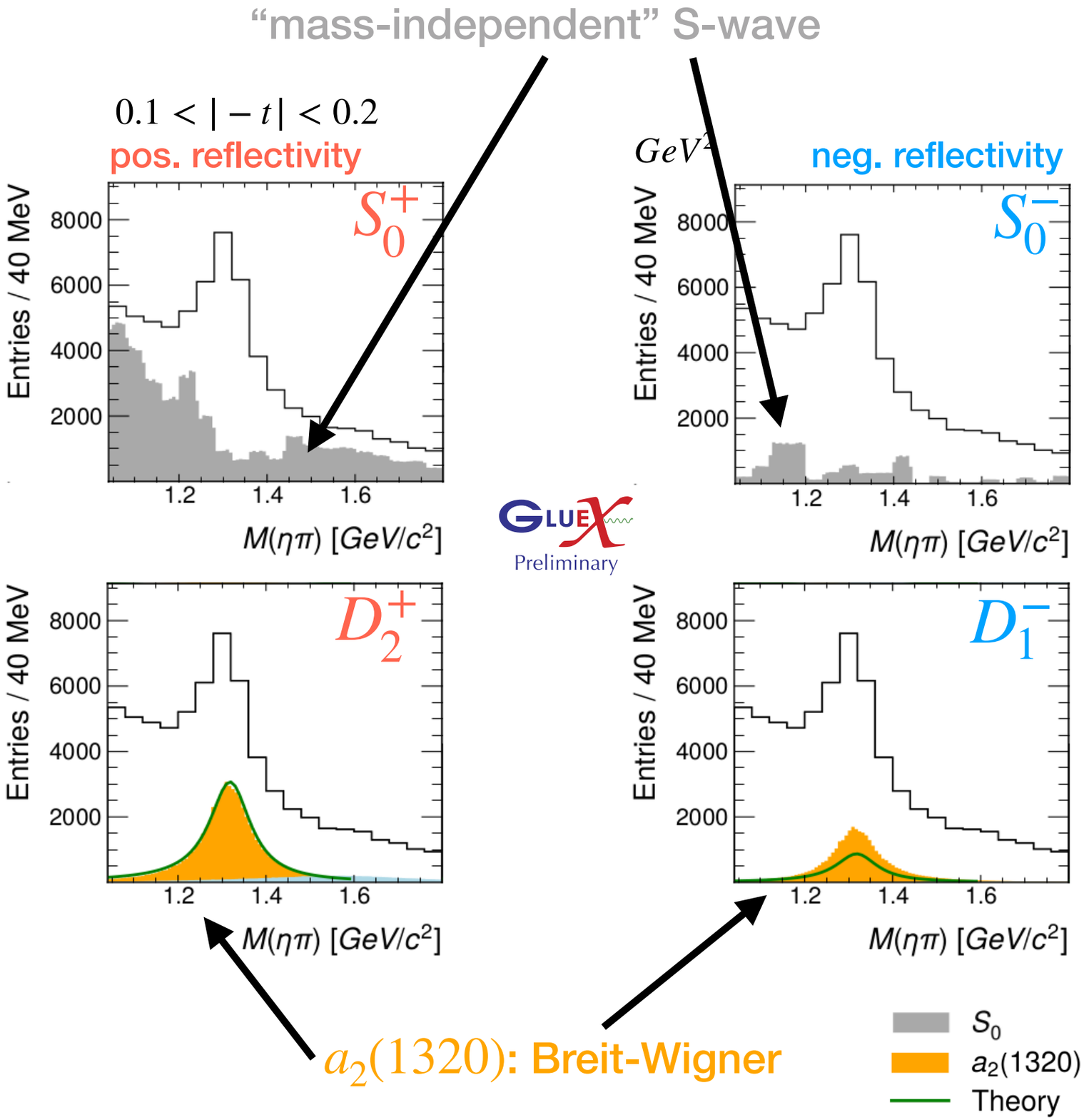
- Persisting challenges:
  leakage between waves, fluctuations - especially for sub-dominant waves, ambiguities

(see also talk by Wyatt Smith Thu, 6/8 2:35pm!)

→ **Perform semi - mass independent PWA to extract a_2 contribution**

Semi-Mass Independent PWA ($\gamma p \to \pi^0 \eta p$)

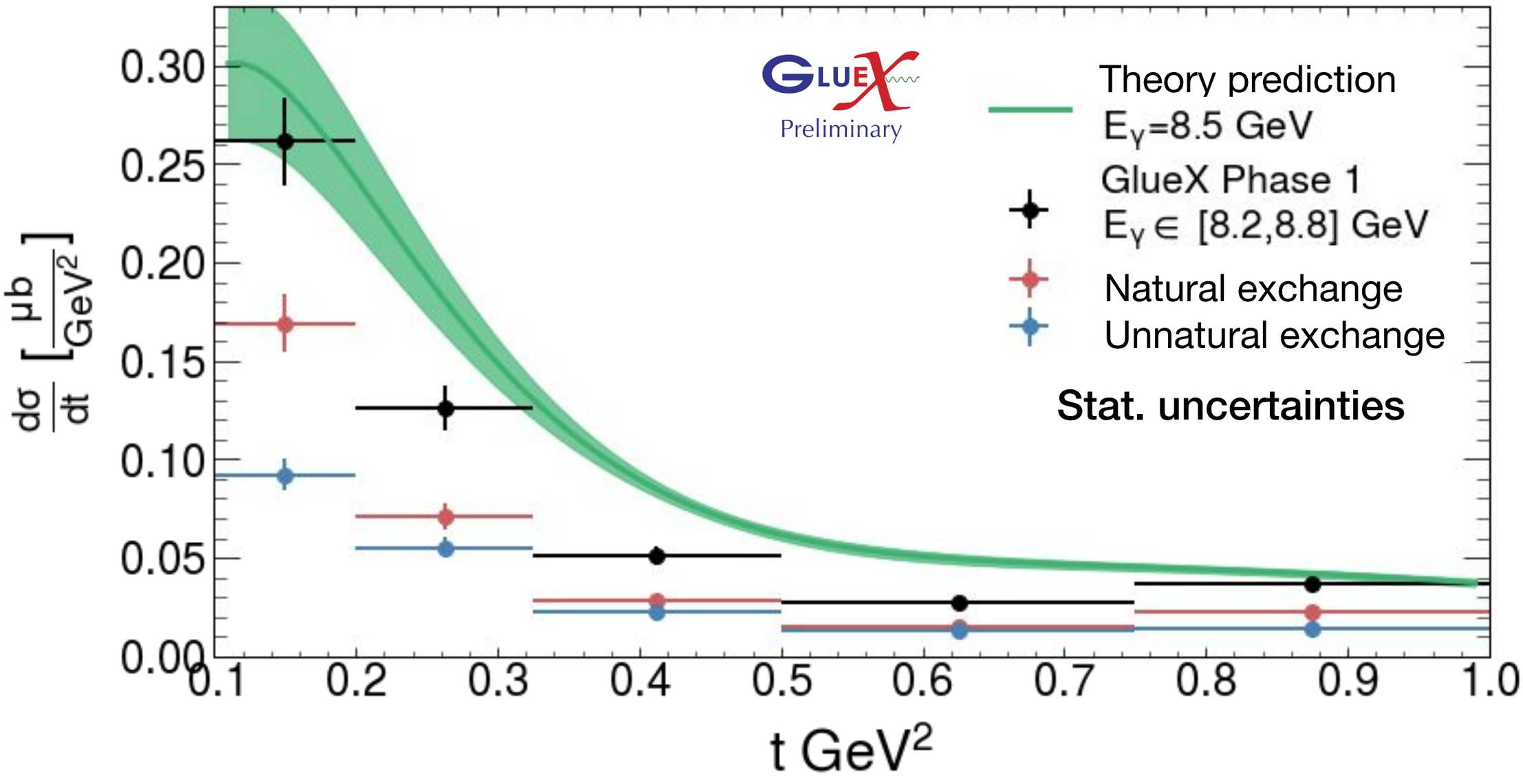
- Simplify problem by introducing physics constraint:
- $a_2(1320)$ reasonably isolated
  → Well described by Breit-Wigner function
- S-wave has complex structure
  → keep "mass-independent" parameterisation



- Eliminates leakage between waves, ensures continuity of solution
- Major contributions consistent with observations from mass independent PWA

Differential $a_2(1320)^0$ Cross Section

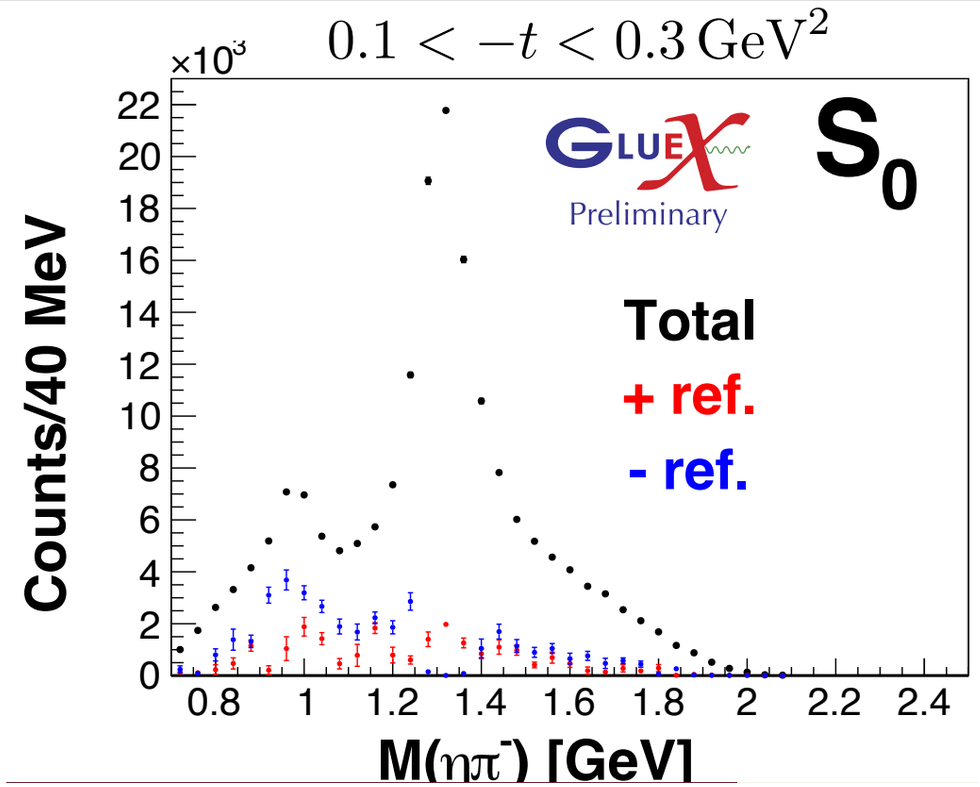
- Including $a_2(1700)$ has impact on result, tail underneath $a_2(1320)$
  → More sophisticated model being tested together with JPAC
- Good agreement with theory prediction
- Publication in preparation

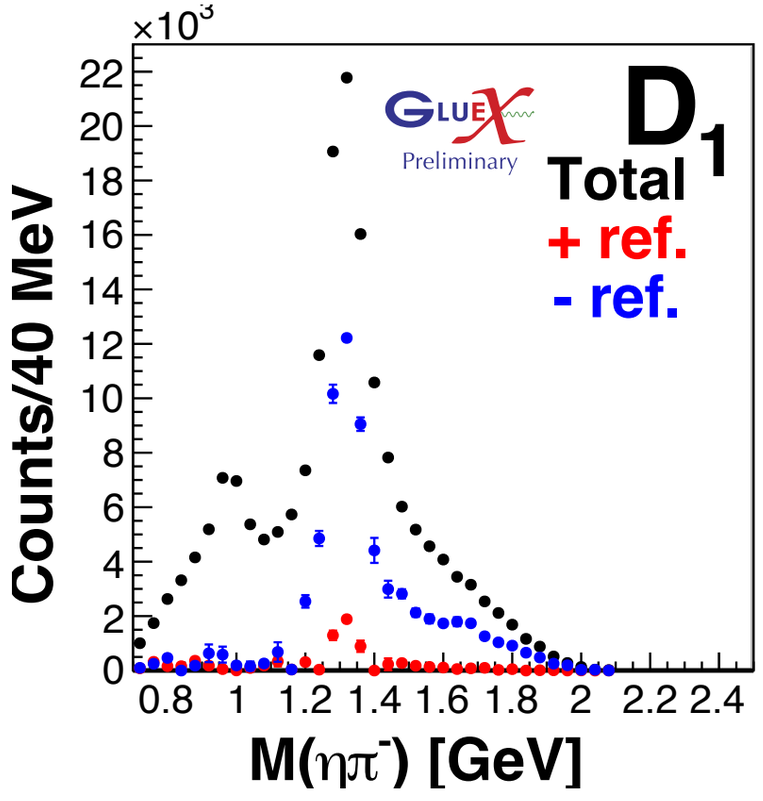


Mass Indep. PWA of $\gamma p \to \pi^- \eta \Delta^{++}$ at low t

- Combined fit of all polarization orientations
- Dominant S-wave contribution in negative reflectivity component
- Clear $a_2(1320)$ signal in $m = +1$ D-wave, negative reflectivity
  - Expected for unnatural parity exchange ***(pion exchange! Contrary to neutral channel)***
- Tail in D1 wave related to $a_2(1700)$?
- Same challenges with mass-independent fit as in neutral channel

→ **Extract a_2 cross section with same semi mass-independent PWA stategy**





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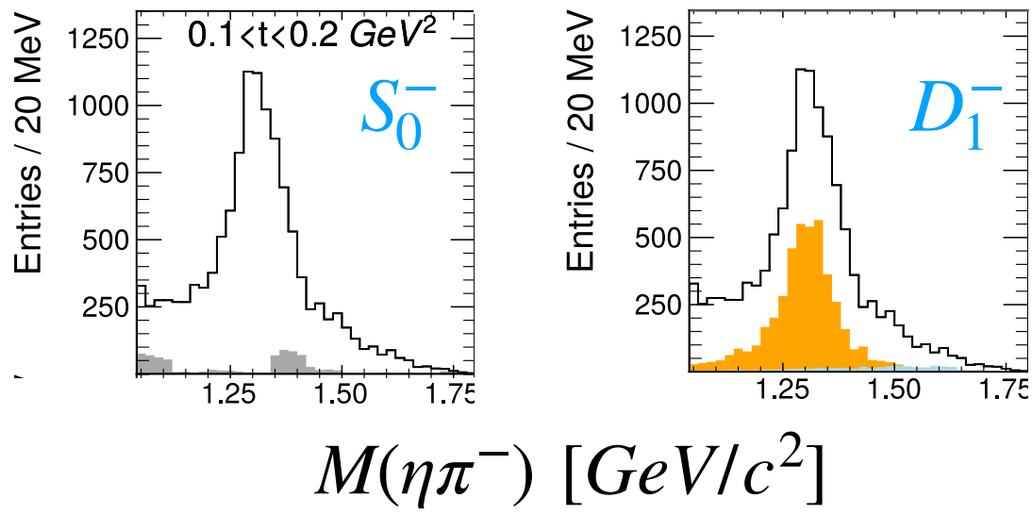
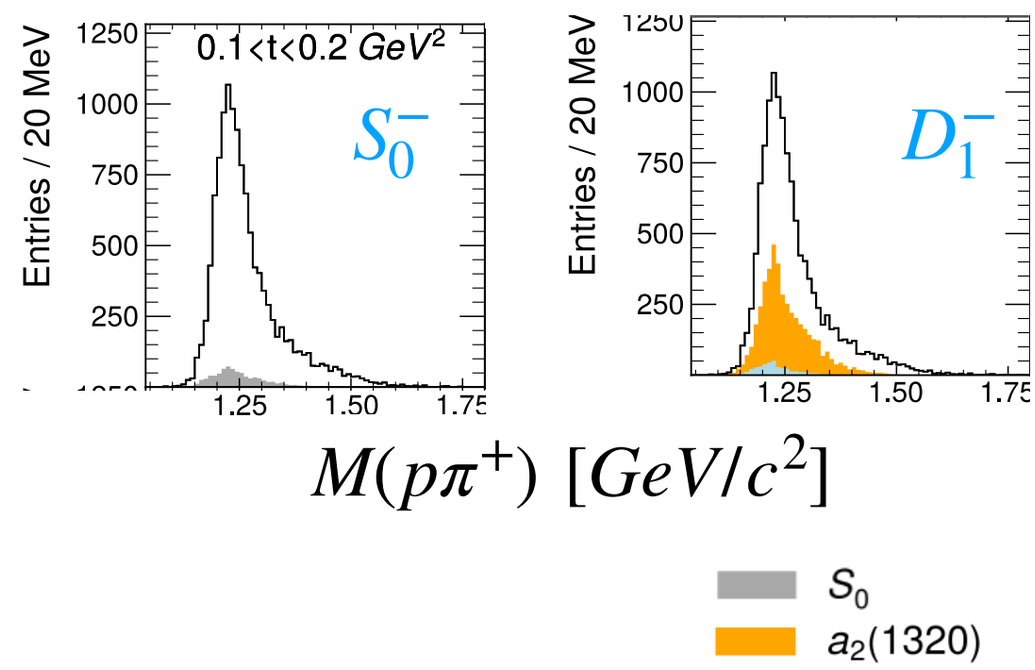
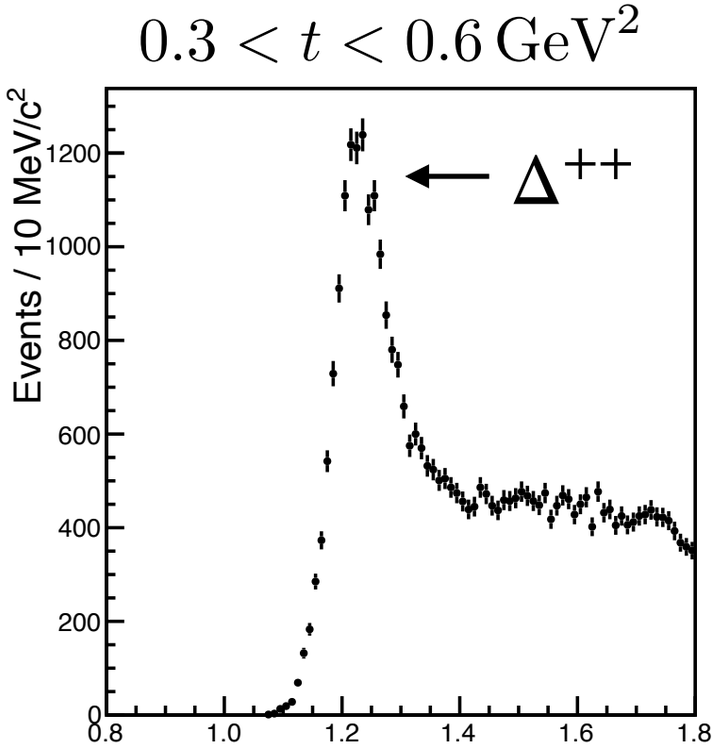
Example projections:

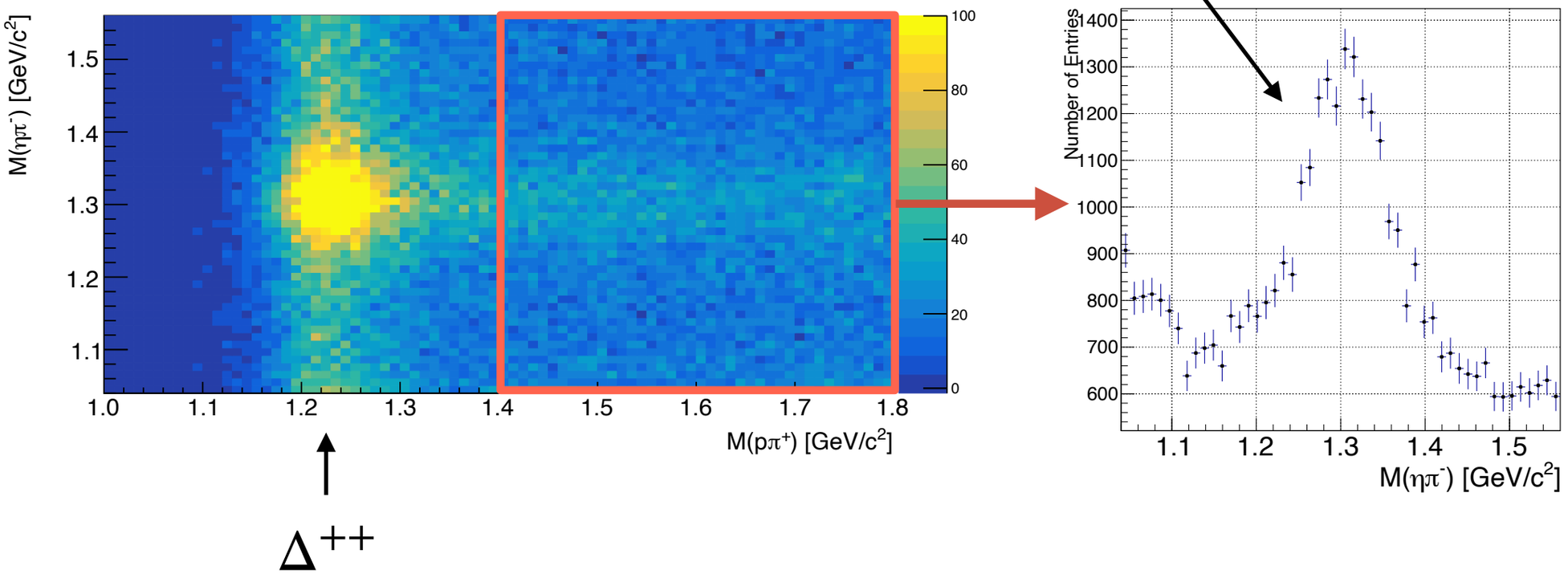




Non-Δ^{++} Background at higher |t|

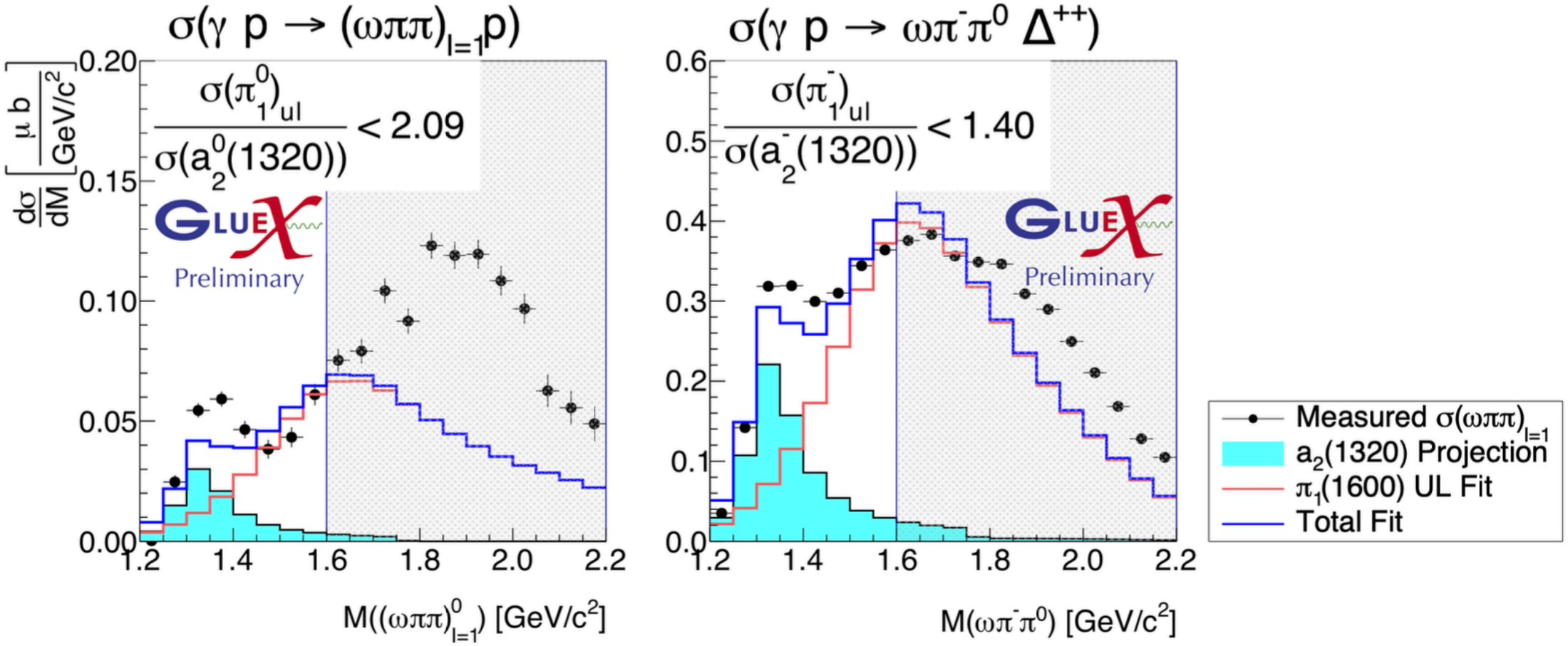
- At higher t, non-Δ^{++} background important
- Contains peaking background under a_2 signal possibly from $\gamma p \to (a_2^- \pi^+)\ p \to \pi^+\pi^-\eta\ p$
- Strategy developed:
  - Include Δ^{++} in amplitudes → working with JPAC
  - Separate components in fit
- Development important for other channels such as $\eta'\pi^-\Delta^{++}, \omega\pi^-\Delta^{++}$



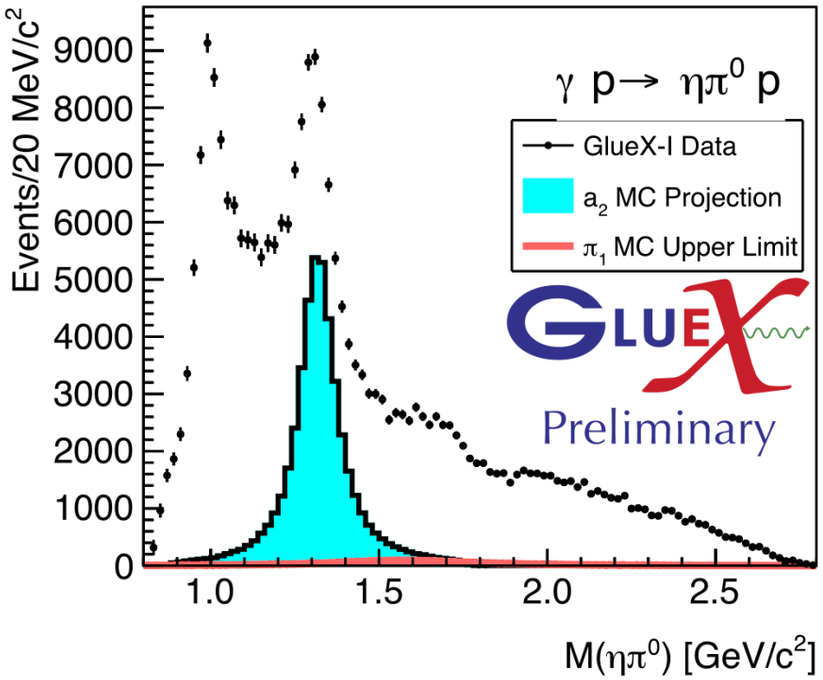


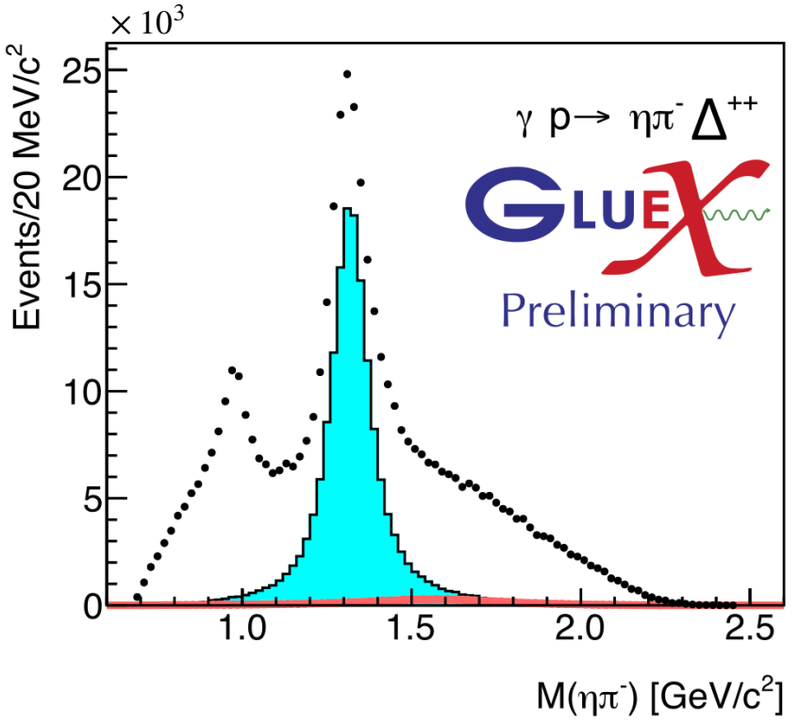
Projection for $\pi_1 \rightarrow \eta^{(\prime)}\pi$

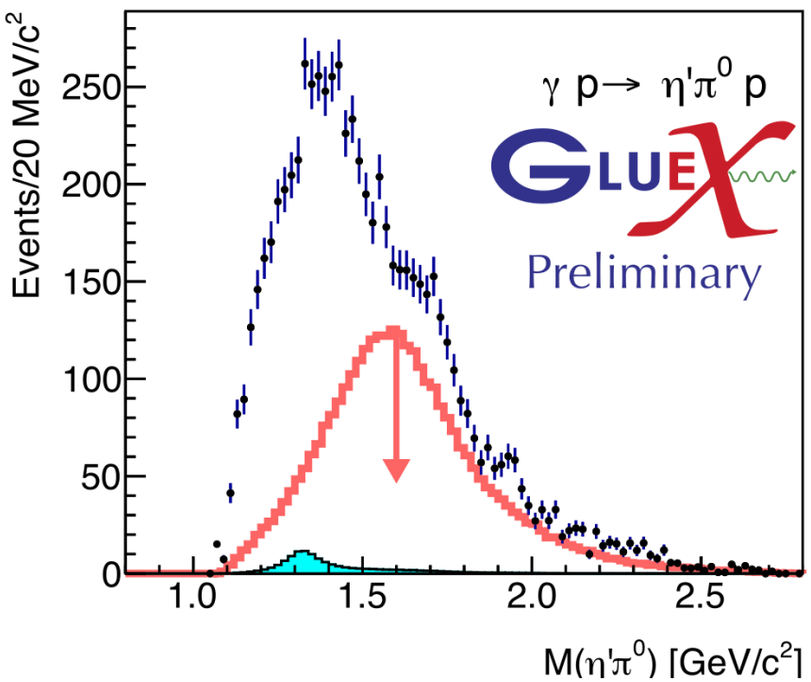
- Measurement of strong a_2 signal in $\eta\pi$ channels serves as reference
- Fit π_1 yield assuming signal saturates measured $I = 1 \quad \omega\pi\pi$ cross sections`

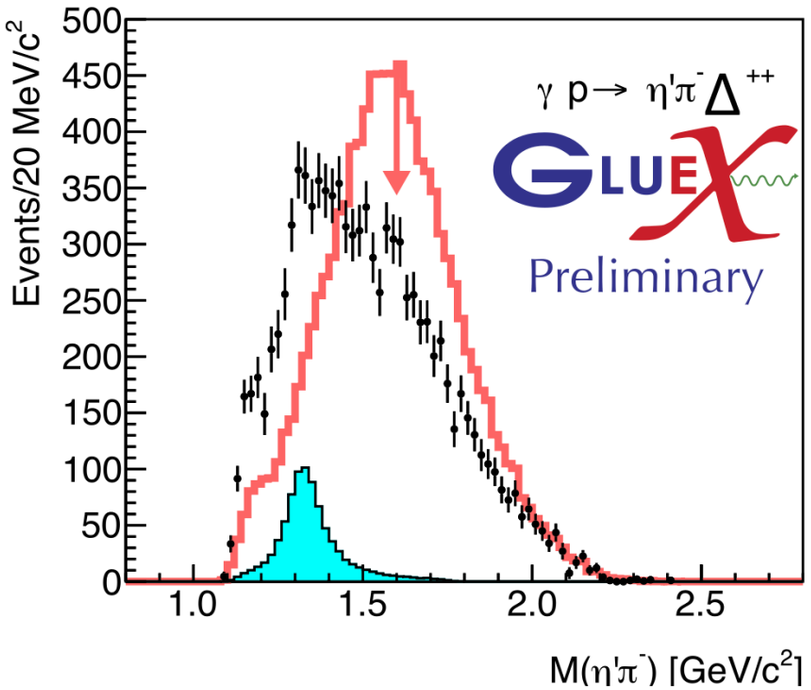


Analysis of $\eta'\pi$ Channels









- Based on upper limit for π_1 cross section from $\omega\pi\pi$:
- No large π_1 signal expected in $\eta\pi$
- Possibly dominant signal in $\eta'\pi$

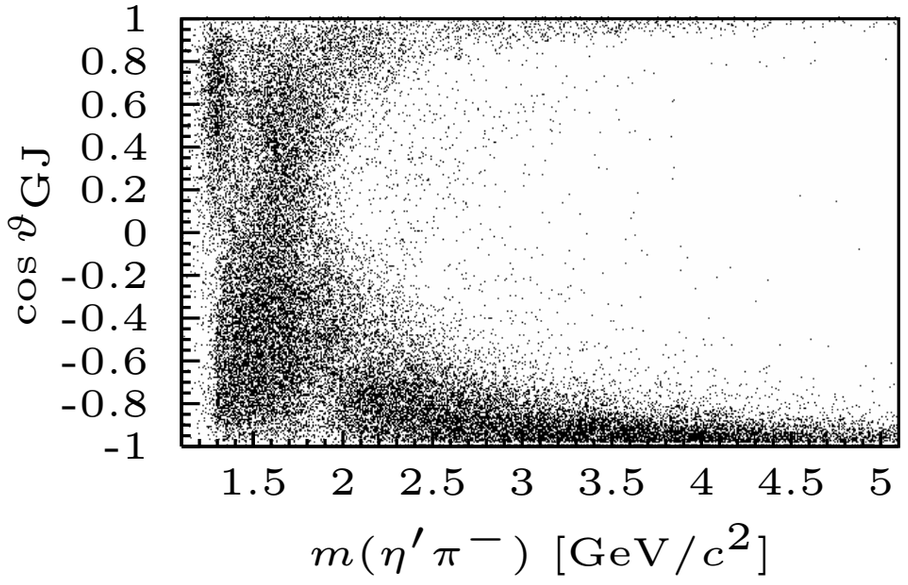
Closeup of $\eta'\pi^-$ Spectra

- Projections look intriguing
- Interesting interference pattern visible

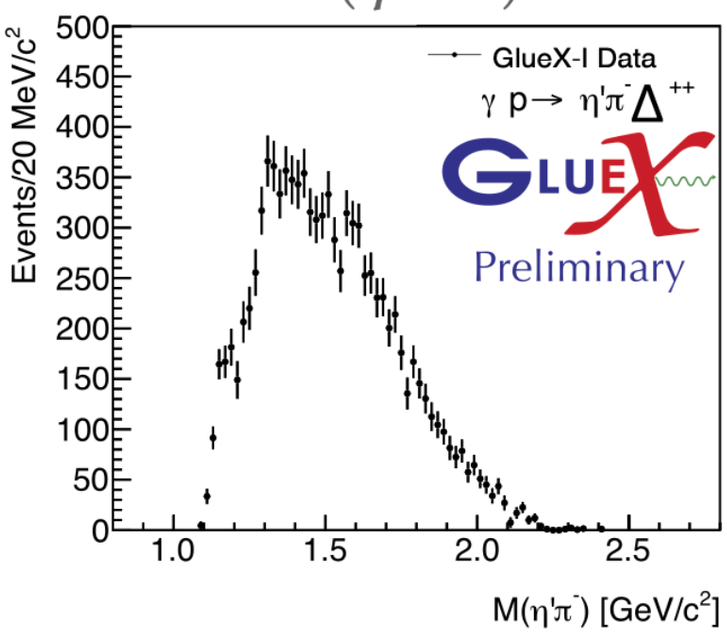
  → Constructive / destructive interference of odd and even wave contributions in different $\cos\theta_{GJ}$ regions?

- Using a_2 cross section measurements from $\eta\pi$ channels as important reference

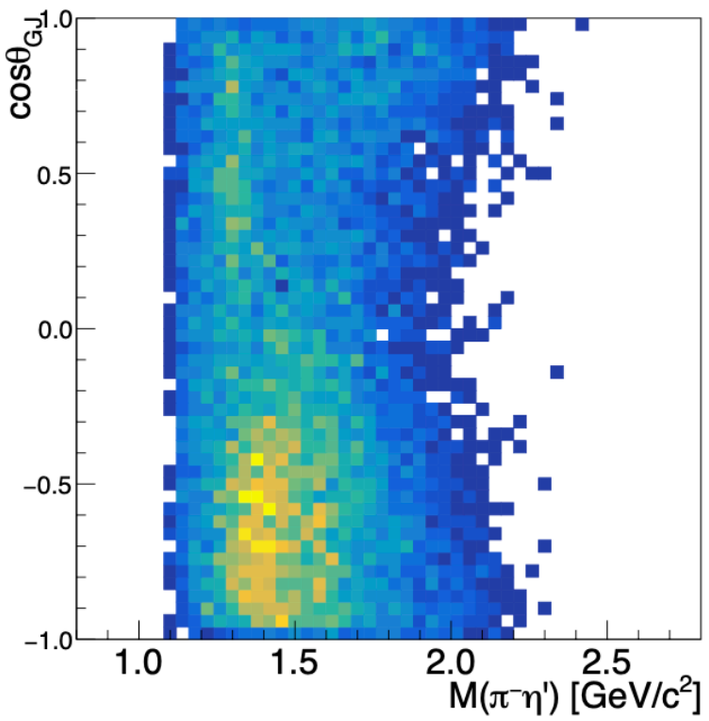
[COMPASS, PLB 740(2015) 303-311]



$m(\eta'\pi^-)$



$\cos\theta^{\eta'}_{GJ}$ vs. $m(\eta'\pi^-)$



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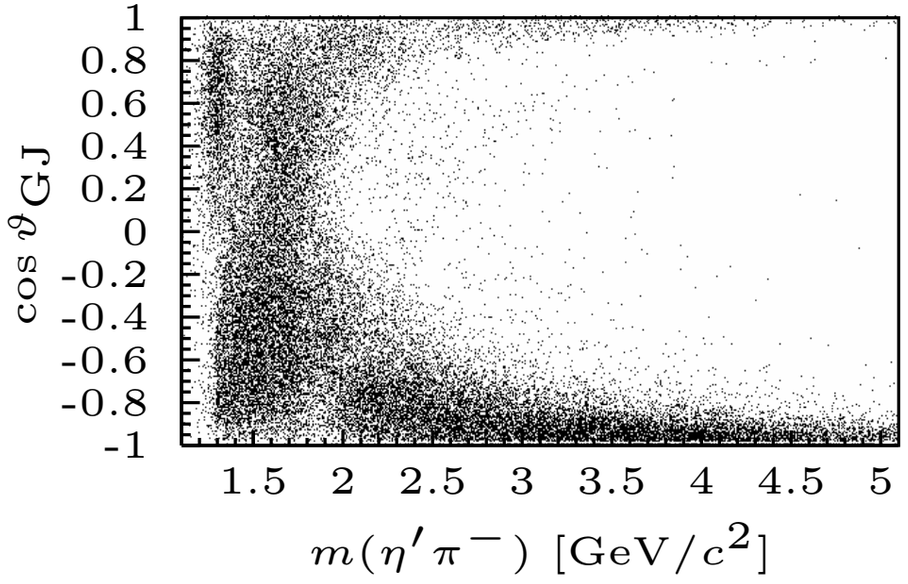
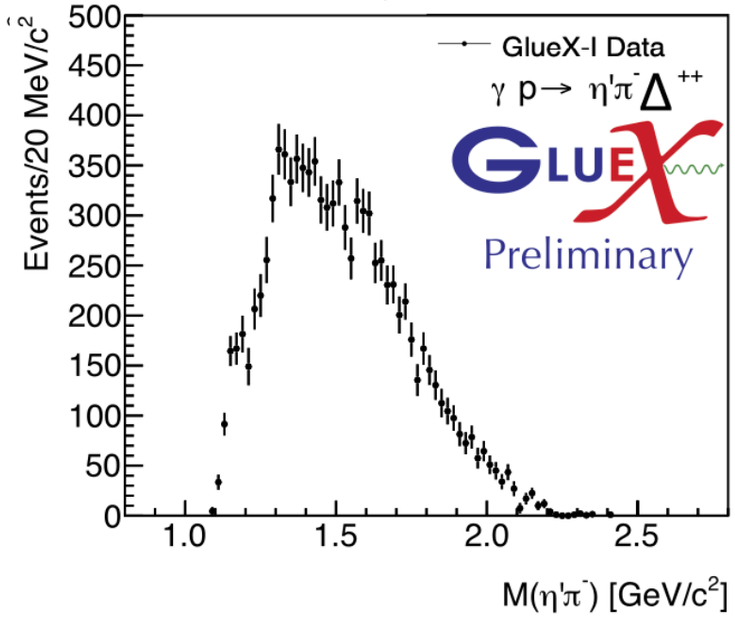
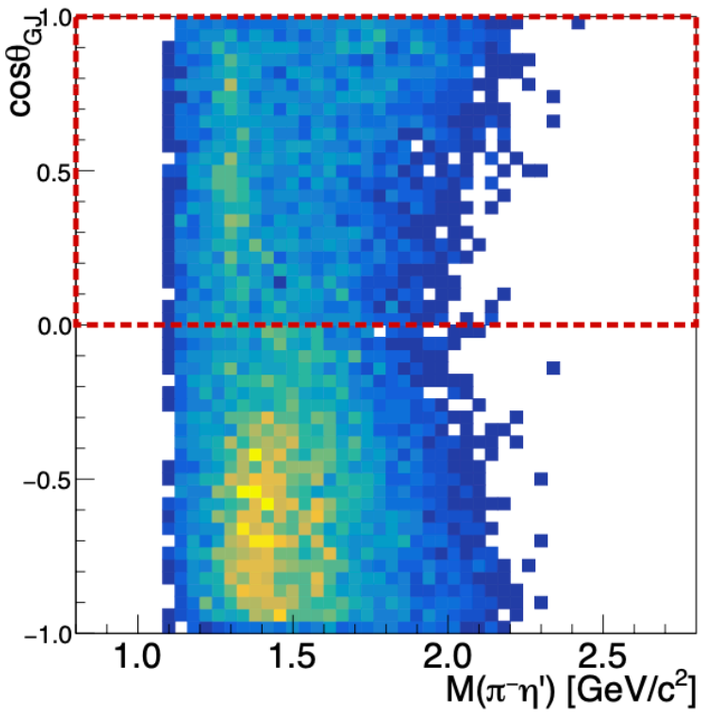


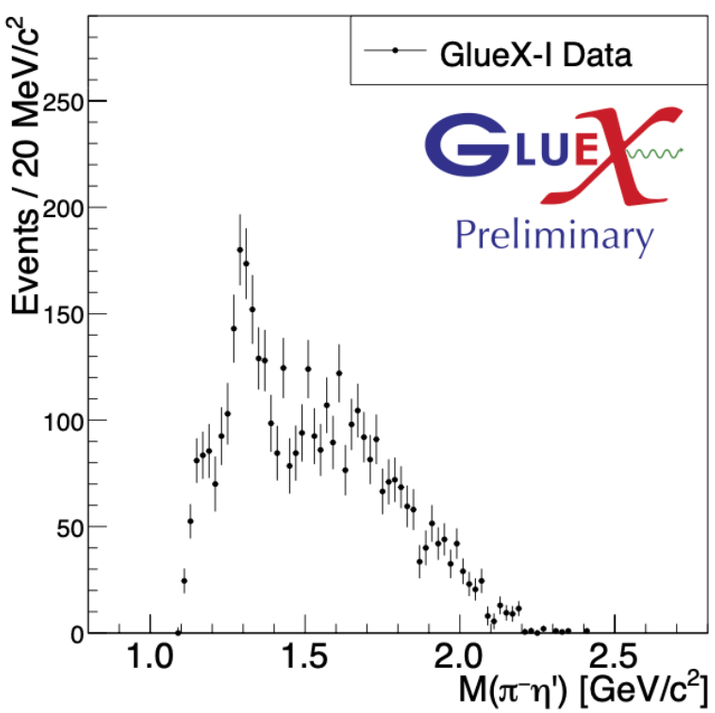
$m(\eta'\pi^-)$



$\cos\theta^{\eta'}_{GJ}$ vs. $m(\eta'\pi^-)$



$m(\eta'\pi^-)$ for $\cos\theta^{\eta'}_{GJ} > 0$



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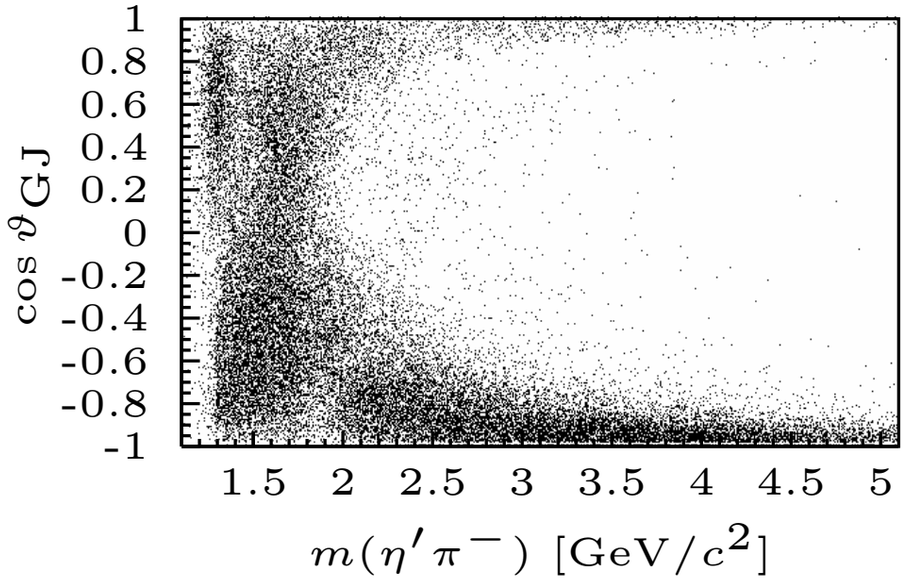
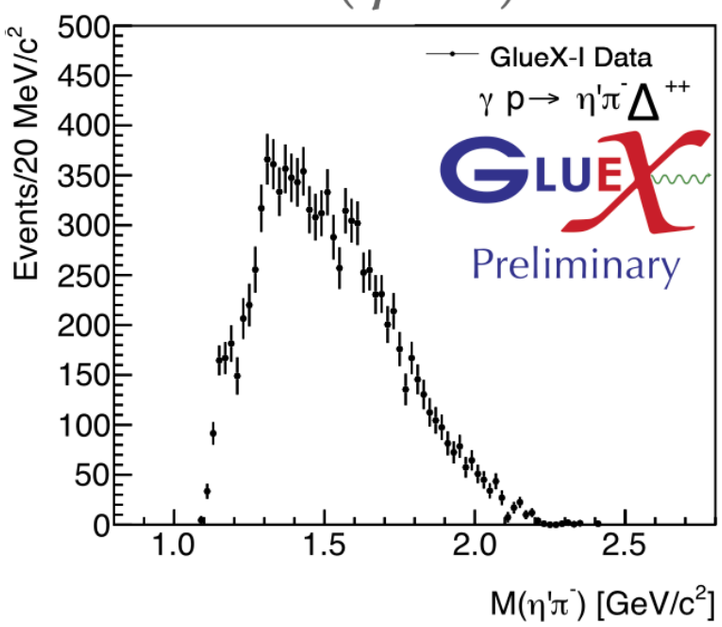
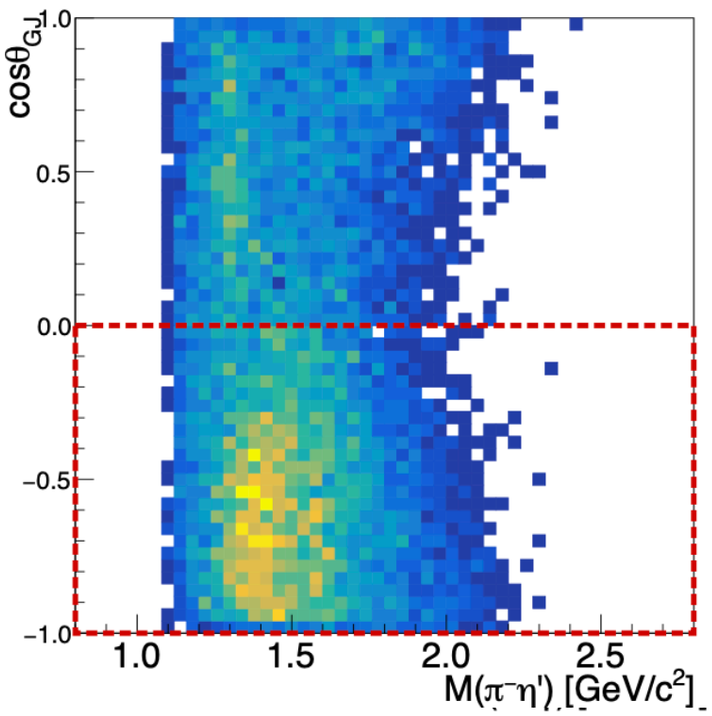


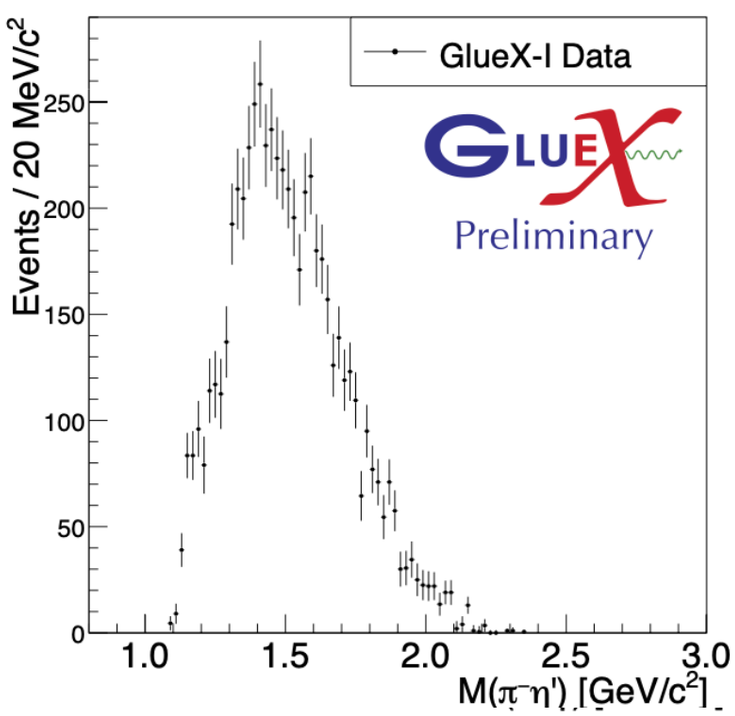
$m(\eta'\pi^-)$



$\cos\theta^{\eta'}_{GJ}$ vs. $m(\eta'\pi^-)$



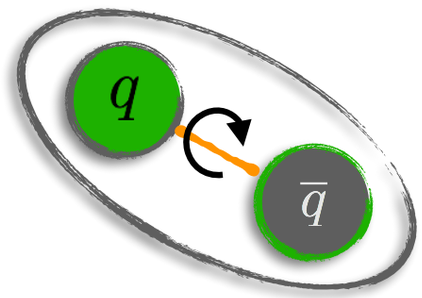
$m(\eta'\pi^-)$ for $\cos\theta^{\eta'}_{GJ} < 0$



Summary and Outlook

- **High quality photoproduction data sets (GlueX Phase I) available, analyses underway**
  - Extract a_2 cross sections in high-statistics $\eta\pi$ channels using PWA and fits with physics constraints,
    use polarization information to investigate production mechanism
    (publication in preparation)
  - Route towards $\eta'\pi$ channels set, analyses underway
    → Use a_2 signal and cross section measurements as reference
  - Partial wave analysis tools being used and further developed
    → Future: Higher statistics (GlueX Phase II, coupling of channels, …)
    will allow to refine analysis strategy and possibly decrease model dependencies

- **Highly productive collaboration with theory (JPAC)**
  (see also talk by Adam Szczepaniak, Tue 12pm!)

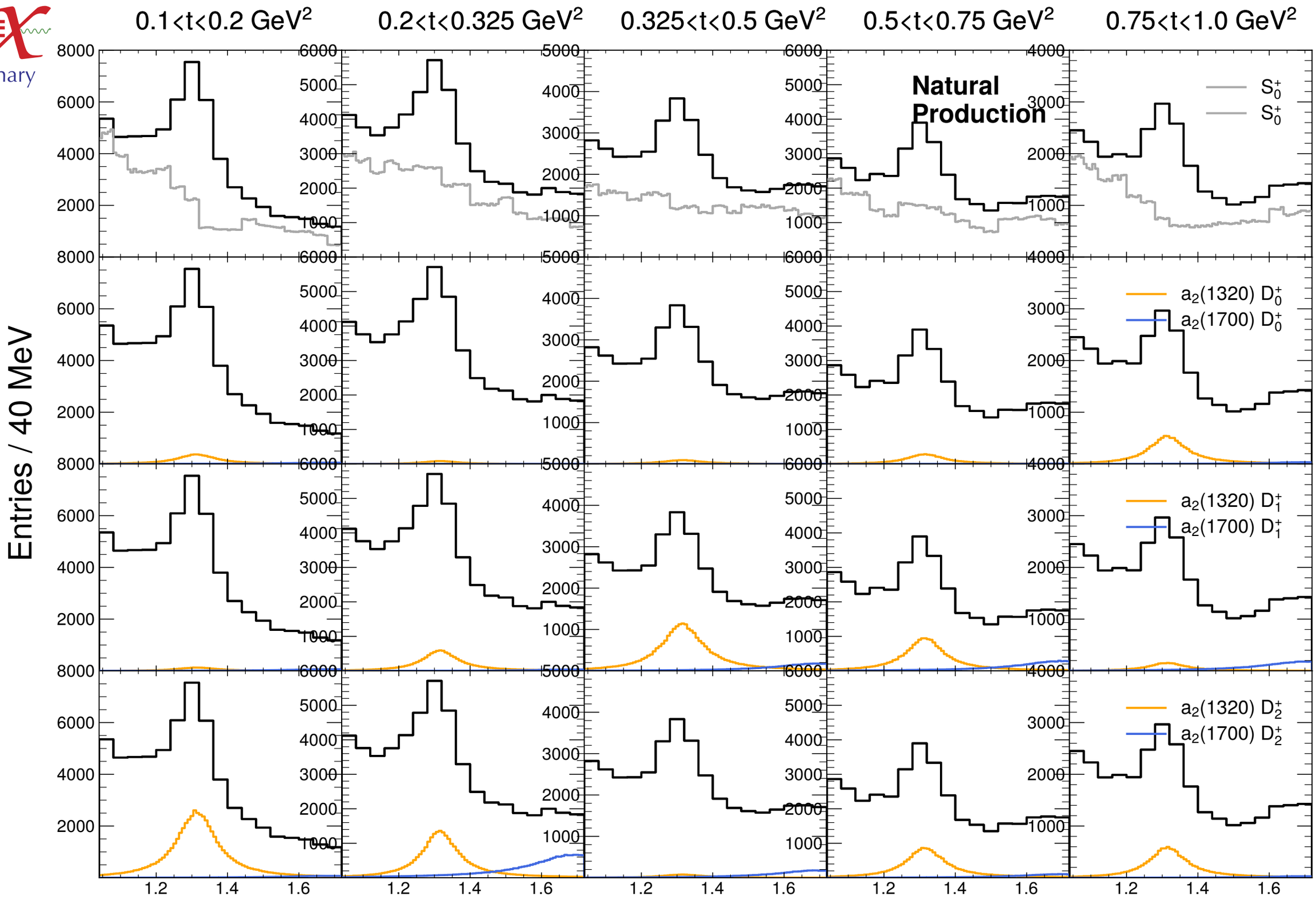


En route to first results on exotic mesons with GlueX!

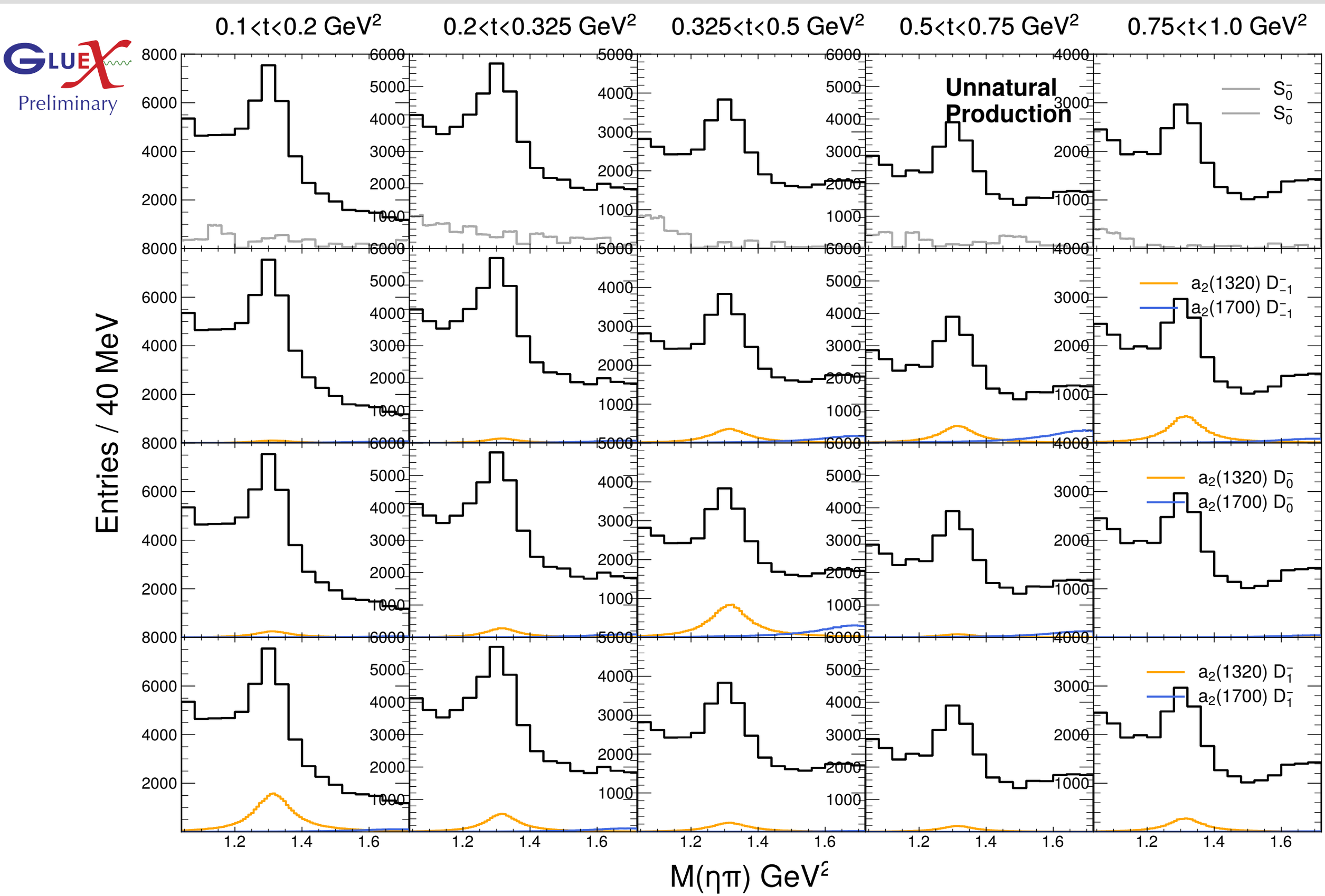
Backup

Semi-Model Independent Fit ($\gamma p \to \pi^0 \eta p$)

GlueX Preliminary

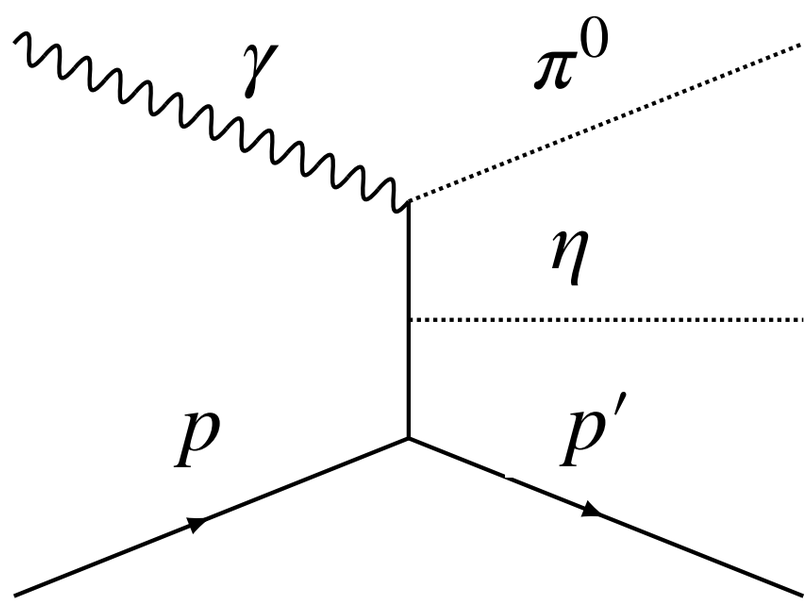


Semi-Model Independent Fit ($\gamma p \to \pi^0 \eta p$)

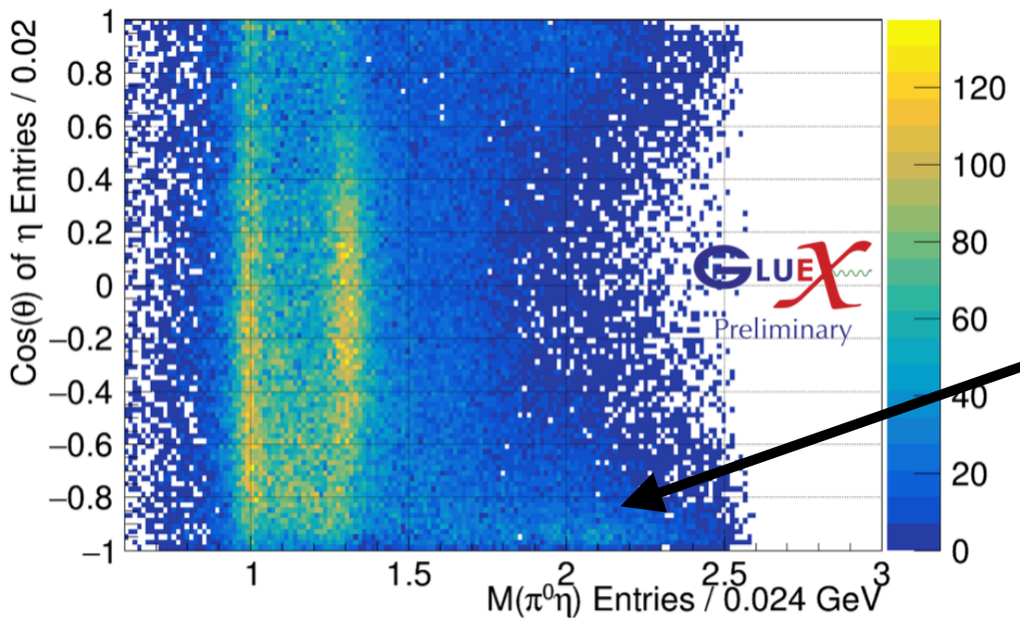


Double Regge Process

- Double-Reggeon exchange process (similar to Deck-contribution at COMPASS)
  - Dominant at high $|t|$ and invariant mass
  - Extends down into resonance region, will overlap with (broad) π_1 signal, if present
  - Can enhance odd partial waves
    → mimic exotic signal



- Important to understand and model this process
  → Theory support indispensable

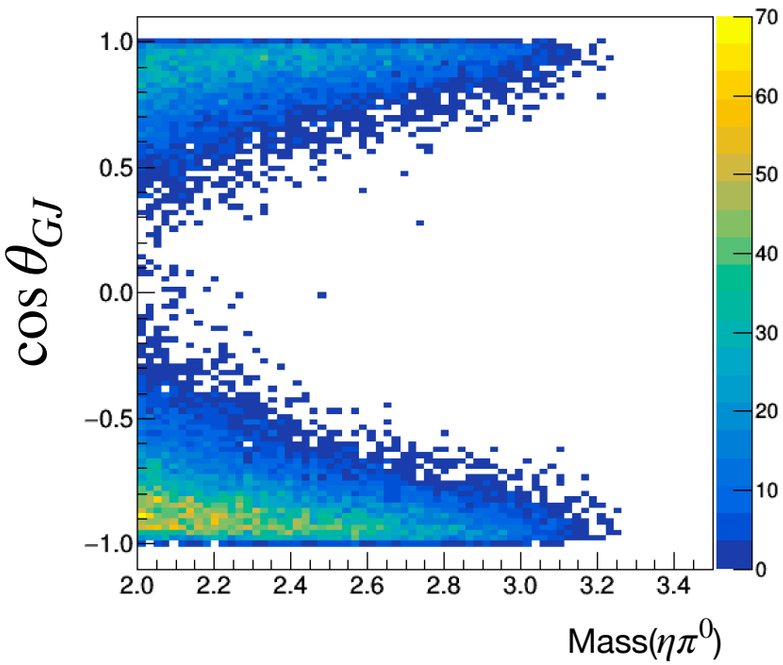


Improved Double Regge Process Modeling

- Close collaboration with Theory/JPAC:
  - Original model was too simplistic
    (see also [L. Bibrzycky et. al. (JPAC), EPJ C 81, 647 (2021)])
  - Improved model available that involves better description of vertex factors, five parameters to describe kinematic distribution
- Monte Carlo study with updated model underway
  - Asymmetric $\cos\theta_{GJ}$ - shape can be reproduced
- First fits to data promising
  - Reasonable agreement in high mass region

→ Can we extrapolate a model for Double Regge to the resonance region?

Generated model MC:



Fit to GlueX data:

Mass($\eta\pi$) : 2.6- 2.7 GeV